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Original Article

Surgical Precision in Dental Implant Placement: Comparing Freehand and Guided Techniques Near the IAN

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ABSTRACT

The rise in the number of dental implants has resulted in a proportional increase in reported complications. These may range from restorative issues caused by inaccurate placement to injury of nearby anatomical structures such as nerves or adjacent teeth. Most of these complications can be prevented by placing implants in an optimal position with precision. Hence, this in vitro pilot study aimed to assess the influence of freehand (FH) and fully guided (FG) surgical techniques on the precision of implant placement near critical structures like the inferior alveolar nerve (IAN). Cone-beam computed tomography (CBCT) and intraoral scans from six individuals with prior mandibular implants were utilized. Ideal implant positioning was digitally planned, and FG surgical guides were produced for each case. Three-dimensional resin models were printed, and implants were inserted using both FH and FG methods on corresponding models. The study measured angular deviation and the distance between the implant apex and the IAN. FH placement showed mean deviations of 1.10 mm coronally, 1.88 mm apically, and up to 6.3° angular deviation, whereas FG surgery demonstrated deviations of 0.35 mm coronally, 0.43 mm apically, and 0.78° angularly. The furthest distance between the implant apex and the IAN was 2.55 mm for FH and 0.63 mm for FG. Within its experimental limitations, this bench-top study indicated both FH and FG techniques can achieve acceptable surgical accuracy for implant placement near the IAN if a 3 mm safety margin is maintained. However, FG surgery—particularly using the R2 Gate® system—showed superior control and lower angular error.

Keywords: Sustainable materials, Dental implants, Inferior alveolar nerve (IAN), Freehand surgery, Fully guided surgery, Surgical accuracy

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Introduction

Dental implant surgery has become a routine and reliable procedure for restoring oral function following tooth loss caused by trauma, edentulism, or resective surgery. With growing demand, several techniques have been developed for managing complex implant cases [1]. However, the surge in implant numbers has paralleled an increase in reported complications. These range from positional restorative errors to trauma to vital structures, including nerves and adjacent teeth. In some cases, nerve damage has led to chronic neuropathic pain and severe psychological distress, including suicidal ideation [2]. Many of these biological, mechanical, and technical complications can be minimized through meticulous planning and precise implant placement [3].

Recent progress in cone-beam computed tomography (CBCT) and intraoral scanning technologies has facilitated digital implant workflows (DWFs). These allow virtual planning of implant positions in three dimensions for both aesthetic and functional optimization. The adoption of digital workflows in oral and maxillofacial surgery is expanding into procedures such as orthognathic corrections, bone regeneration, and zygomatic implant placements, where accuracy and precision are critical [4]. For predictable, long-term treatment success that meets patient expectations, a prosthetically guided three-dimensional planning approach is essential [5]. DWFs improve diagnostic visualization, support backward planning, and enhance both safety and predictability in implant placement.

Nonetheless, factors such as manufacturing inaccuracies and human error must still be accounted for to avoid damage to key anatomical structures [6]. Accurate positioning provides adequate bone support and proper load distribution. Although freehand (FH) surgery has traditionally been the most common approach [5, 6], its accuracy is operator-dependent. Even when aided by stents or anatomical landmarks, FH surgery requires advanced spatial judgment and significant surgical skill to place implants correctly within limited bone dimensions [7, 8]. Consequently, standardization is difficult, and clinical outcomes vary.

Fully guided (FG) implant surgery, utilizing virtual 3D planning and printed guides, offers a promising alternative for enhanced safety, precision, and reproducibility. Evidence from a systematic review indicates that implants placed using digital static guides exhibit five-year survival rates comparable to the general survival rate of 95.6%, despite involving complex cases [6]. However, definitive data on the surgical precision of FG methods remain limited. In FG surgery, 3D printed guides contain sleeves for drills of increasing diameter, enabling controlled osteotomy preparation and implant placement that mirror the planned position [9, 10]. According to researchers *et al.* [11], this approach provides the highest accuracy, showing mean coronal global deviation (CGD) of 0.73 mm, apical global deviation (AGD) of 0.97 mm, and angular deviation (AD) of 2.30°, confirming FG as a gold standard for implant positioning.

Accurate implant placement is crucial and can be attained through the use of anatomical landmarks and basic surgical stents to achieve optimal aesthetics while preventing injury to critical structures such as tooth roots and nerves. Misplacement of implants increases the likelihood of peri-implantitis due to improper prosthetic design and excessive loading forces [7]. Moreover, trauma to the inferior alveolar nerve (IAN) can be severe, long-lasting, and significantly impact a patient's quality of life. The R2 Gate® software allows quantitative identification of the IAN by measuring Hounsfield units (HU) [8], enabling clearer distinction from adjacent bone compared with the subjective interpretation of cone-beam computed tomography (CBCT) scans. Although a 2 mm safety margin has been widely accepted to avoid IAN injury [9, 10], Renton (2010) suggested that this distance might be insufficient because the drill tip extends approximately 1.5 mm beyond the implant apex [2]. Greenstein and Tarnow (2006) therefore proposed a 4 mm safety zone to compensate for the drill's length, enabling highly precise implant placement and minimizing the potential for nerve damage [11].

The present study aimed to determine whether fully guided (FG) implant surgery allows for greater surgical precision than freehand (FH) methods, particularly in minimizing the risk of harm to nearby anatomical structures like the IAN. FG surgery, which utilizes virtual 3D planning, is believed to enhance the accuracy, safety, and efficiency of implant placement. The FG technique uses a 3D printed guide fitted with a sequence of drill sleeves corresponding to increasing drill diameters for osteotomy preparation [12, 13]. In this study, implants were placed through these guides to replicate the digitally planned position, thereby allowing assessment of the method's surgical accuracy [14].

Materials and Methods

This experimental bench study employed a fully digital workflow to virtually design implant placements within stereolithographic mandibular models, aiming to compare the accuracy of the FG implant placement method with conventional FH drilling. Ethical clearance was granted by the University of Salford Ethics Committee (HST1920-007).

Eligibility criteria for case selection

CBCT scans from six patients treated at the ICE Postgraduate Institute and Hospital were utilized to create stereolithographic mandibular models for implant insertion. The inclusion criteria consisted of patients with intact premolar or molar regions in the mandible, sufficient bone height between the alveolar ridge and the IAN to allow a 4 mm safety margin for a 10 mm implant, and a minimum distance of 1.5 mm from adjacent teeth as well as between the implant shoulder and the buccal bone. Exclusion criteria included cases where the full trajectory of the IAN canal or mental foramina could not be clearly traced by the practitioner, or where incidental findings or pathological conditions were detected on the CBCT scans.

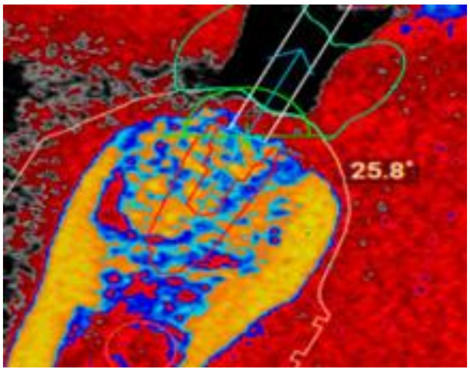
Each case involved the planned placement of a single implant-retained crown using a 4.0 × 10 mm Megagen AnyRidge® (Bedfordshire, UK) implant positioned in an ideal restorative location with sufficient surrounding bone for long-term success. **Table 1** summarizes the selected case categories. For every case, the corresponding STL files and CBCT datasets were uploaded into the R2 Gate® platform to enable 3D virtual planning, following standardized protocols to ensure consistency across all models.

Table 1. Description of selected case categories. Abbreviations: lower left (LL), lower right (LR), inferior alveolar nerve (IAN).

Case Number	Description of Selected Cases
Case 1	Absence of lower right first molar, bounded saddle, socket preservation performed, inferior alveolar nerve (IAN) positioned inferiorly
Case 2	Lower right first molar missing, bounded saddle, socket preservation done, IAN located inferolaterally
Case 3	Lower right first molar absent, socket preservation completed, IAN situated inferiorly
Case 4	Missing lower left second molar, socket preservation performed, IAN inferior, lower left first molar also absent, wider guide span between bounded saddles
Case 5	Lower right first molar missing, bounded saddle, socket preservation done, IAN inferolateral, lingual bone inclined laterally
Case 6	Lower left first molar absent, bounded saddle, socket preservation completed, no lingual fossa present, IAN inferolateral and near the planned implant site

3D protocol planning

Sectional CBCT scans of patients' mandibles were obtained using a MORITA (Veraviewepocs) unit with a 5 × 5 cm field of view (FOV) during routine implant assessment. Digital surface models (STL files) were produced from intraoral optical scans (IOS) that captured teeth and soft tissue anatomy via the Trios/3Shape® system (Straumann, UK). These STL datasets were integrated with CBCT data, and the inferior alveolar nerve (IAN) was delineated using Megagen R2Gate® planning software (www.r2gate.com, accessed 10 May 2021). Bone density values in Hounsfield Units (HU) were employed to trace the IAN path—ranging from >1250 HU for dense cortical bone (D1) to 350–150 HU for trabecular bone. The R2Gate Digital-EYE function translated 256 grayscale shades into a color-coded bone density map, assisting in the selection of an appropriate drilling sequence **(Figure 1)**. After virtual validation, two stereolithographic models per case were printed from STL files using an EnvisionTEC Vida printer (Dental 3D Printers, Dearborn, MI, USA) [10].



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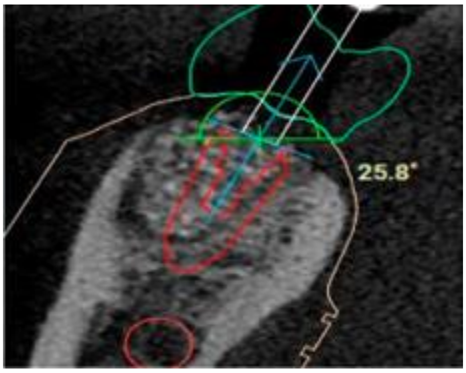

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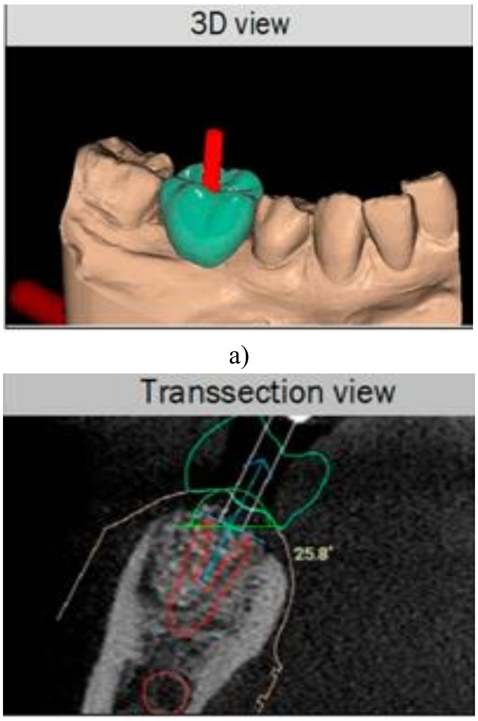
Figure 1. (a) Color mapping of HU values and (b) identification of anatomical structures. Yellow represents bone, red represents soft tissue, allowing precise tracing of the IAN.

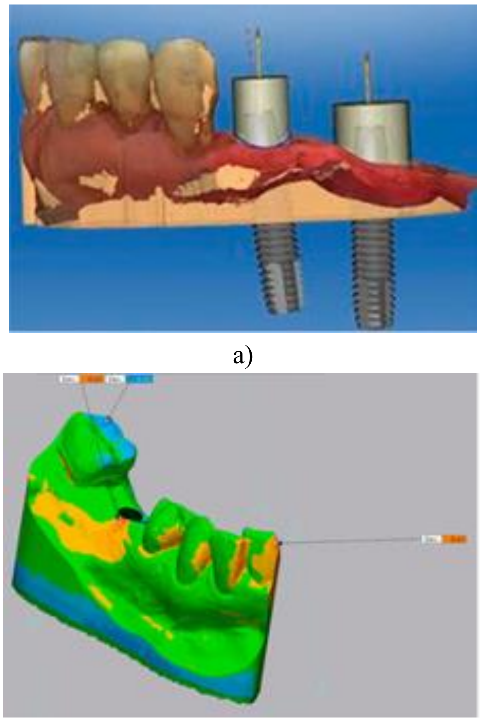
The printer achieved a precision level of 30 µm using e-guide tint resin, ensuring reproducible model fabrication [15]. Each implant was selected from the R2Gate® library and positioned restoratively in close proximity to the IAN and mandibular nerve (MN) according to the virtual design. For every model, a Megagen AnyRidge® implant (4.0 mm diameter × 10 mm length) was virtually placed under the following parameters **(Figure 2)**: a minimum 4 mm safety margin from the IAN [16], 1.5 mm spacing from adjacent teeth [17], and 1.5 mm clearance between the implant shoulder and buccal bone plate [18]. The shortest perpendicular distance between the implant apex and the IAN was determined using the software's measurement tool. Both researcher and technician verified the finalized plan.



a)

b)

Figure 2. Virtual visualization of the IAN, safety zone, and planned implant position using Megagen R2Gate®.



a)

b)

Figure 3. 3D printed STL illustrating model accuracy deviation of less than 0.13 mm for FH placement.

In-vitro implant placement

An experienced implant clinician with a record of over 50 placements performed the implant insertions, as suggested by researchers [19] to ensure operator reliability. For each case, two 3D-printed mandible replicas were used: one for freehand (FH) and one for fully guided (FG) surgery. Implant placement was performed with Megagen AnyRidge® FH and Megagen® Universal FG kits, under sterile water irrigation to prevent resin overheating and maintain dimensional integrity. The FH group relied on visual alignment with the virtual plan, placing implants 2 mm deeper on drill markings to compensate for soft tissue depth [20]. Drilling followed standard Megagen AnyRidge® protocols for both methods, with water rinsing to remove debris from the osteotomy site prior to seating the implant.

Digital scanning of the implants using IOS

After placement, Megagen AnyRidge® scan flags were attached to each implant. The models with scan flags were scanned using a laboratory-grade scanner (model specifications required) to create STL datasets representing the final implant positions **(Figure 3)**.

Scan analysis using EXOCAD®

The resulting STL files were imported into Exocad dental CAD software, where digital Megagen AnyRidge® 4.0 × 10 mm implants were virtually aligned to the scan flag positions to visualize the actual implant placement. These updated STL models were exported and subsequently analyzed in R2Gate® software to compare the placed implants with the planned positions [21, 22].

Measurement of deviations in implant position

Overlay analyses were conducted using Geomagic Control software, which has demonstrated reliability in prior implant comparison research [23]. The STL of the placed implant was superimposed on the original planned model to measure coronal, apical, and angular deviations. Model alignment accuracy was also verified to ensure that any detected deviations were due solely to implant placement rather than manufacturing discrepancies.

Data analysis

All collected measurements were recorded and analyzed using Microsoft Excel. Since FH and FG placements originated from the same cases, the data were treated as paired samples [24]. The implant neck served as the consistent reference point for both methods. Paired t-tests were performed to compare FH and FG results in coronal midpoint deviation, apical midpoint deviation, angular (vector) deviation, and deviation of implant-to-IAN distance from the planned position. The statistical significance threshold (α) was set at 0.05 for all analyses.

Results and Discussion

When comparing the freehand (FH) and fully guided (FG) approaches using stereolithographic models against the digitally planned implant positions in Geomagic Control Software (3D Systems Corporation, Cary, NC, USA), the deviation summaries are presented in **Tables 2 and 3**. **Table 2** outlines the FH deviations, and **Table 3** summarizes those for FG surgery. Positive deviation values represent implant placements located farther from the IAN, whereas negative values indicate proximity closer to the nerve.

Table 2. Deviation from the planned implant position in FH technique. Positive values = farther from IAN; negative values = closer to IAN.

Case	Free Hand Distance to IAN (mm)	Planned Distance to IAN (mm)	Deviation (mm)	Coronal Deviation (mm)	Apical Deviation (mm)	Angular Deviation (°)
1	3.21	4.28	+1.07	1.00	2.02	8.00
2	2.50	2.79	+0.29	0.87	2.17	9.12
3	6.29	7.91	+1.62	1.88	2.03	1.99
4	4.70	4.93	+0.23	0.70	0.93	4.88
5	4.18	6.73	+2.55	1.69	3.38	11.78
6	1.29	1.22	−0.07	0.44	0.78	2.82
Mean	3.70 ± 1.76	4.64 ± 2.47	0.95 ± 1.00	1.10 ± 0.57	1.88 ± 0.95	6.43 ± 3.82

Table 3. Deviation from the planned implant position in FG technique. Positive values = farther from IAN; negative values = closer to IAN.

Case	Fully Guided Distance to IAN (mm)	Planned Distance to IAN (mm)	Deviation (mm)	Coronal Deviation (mm)	Apical Deviation (mm)	Angular Deviation (°)
1	3.21	2.96	−0.25	0.43	0.53	0.97
2	2.50	3.13	+0.63	0.79	0.92	0.98
3	6.29	6.33	+0.04	0.14	0.14	0.16
4	4.70	4.80	+0.10	0.22	0.22	0.95
5	4.18	4.35	+0.17	0.21	0.21	0.97
6	1.29	1.08	−0.21	0.29	0.29	0.69
Mean	3.70 ± 1.76	3.78 ± 1.80	0.08 ± 0.32	0.35 ± 0.24	0.43 ± 0.27	0.78 ± 0.33

Figure 4 compares the deviation between planned and actual implant positions for both techniques. The mean deviation from the planned position for FG surgery (0.08 ± 0.32 mm) was substantially lower than that of FH surgery (0.97 ± 1.00 mm). Generally, the FH approach tended to maintain a greater safety margin from the IAN, except in Case 6, where the FH implant was placed nearer to the IAN than intended [25]. The FG approach also resulted in slightly closer proximity to the IAN than planned in Cases 1 and 6. Despite this, the FG technique exhibited superior consistency, shown by its smaller standard deviation. Statistically, however, there was no significant difference between FH and FG placements regarding apex-to-IAN distance (p = 0.10).

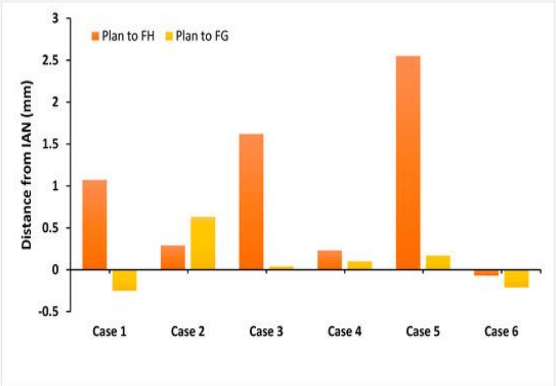


Figure 4. Deviation between planned and actual implant positions, and corresponding distance to the IAN. Negative values denote implants positioned closer to the IAN than intended.

Overall, FG surgery achieved greater accuracy across nearly all measured parameters. The vector angle deviation was significantly lower in FG placements (0.78 ± 0.33 mm) compared with FH (6.43 ± 3.82 mm), yielding p = 0.01. Similarly, apical deviation was significantly reduced in FG (0.43 ± 0.27 mm) compared to FH (1.88 ± 0.95 mm), with p = 0.02. For coronal deviation, although the difference was not statistically significant (p = 0.05), FG still demonstrated smaller deviation values (0.35 ± 0.24 mm vs. 1.10 ± 0.57 mm) [26].

Implant placement precision can vary depending on the clinician's experience and the tools or systems employed [27]. In this controlled bench study, carried out by a single experienced operator, no statistically significant difference was observed between FH and FG placements concerning the apex-to-IAN distance (p = 0.10). However, within study limitations, FG surgery demonstrated higher precision overall, especially regarding angular deviation. This suggests that FG systems could improve operator confidence in avoiding injury to adjacent critical structures. Potential sources of minor FG inaccuracies include 3D printing resolution, post-processing variability, CBCT image quality, and mechanical alignment errors such as drill tube positioning or bone-to-guide spacing. Such factors should be carefully managed when operating near the IAN or similar anatomical features [26, 28].

Comparison with recent literature **(Table 4)** reinforces that FG methods tend to achieve greater positional accuracy than FH approaches. Reported sub-millimeter discrepancies for FG implants—ranging between 0.4–1.4 mm at the entry point and 0.4–1.6 mm at the apex—are consistent with findings of the current study, except for the systematic review by Tahmaseb *et al.* [29]. Across multiple clinical studies involving single operators and patient groups aged 11–59 years, both FH (6.4–9.1°) and FG (0.8–5.0°) angular deviations were observed. The present in vitro study recorded angular deviations under 2° for FG placements, demonstrating higher precision compared with previous reports.

Table 4. Comparison of deviations between planned and actual implant placements for FH and FG methods.

Study	Free-Hand Mean Deviation	Guided Mean Deviation
Fürhauser *et al.* (2015) [30]	-	Entry: 0.8 mm Apex: 1.2 mm Angle: 2.7°
Schnutenhaus *et al.* (2016) [31]	-	Entry: 1.0 mm Apex: 1.6 mm Angle: 5.0°
Tahmaseb *et al.* (2018) [29]	-	Entry: 0.9 mm Apex: 1.2 mm Angle: 3.3°
Vercruyssen *et al.* (2015) [32]	Entry: 2.8 mm Apex: 3.1 mm Angle: 9.1°	Entry: 1.4 mm Apex: 1.6 mm Angle: 3.0°
Younes *et al.* (2018) [33]	Entry: 1.5 mm Apex: 2.1 mm Angle: 7.0°	Entry: 0.7 mm Apex: 1.0 mm Angle: 2.3°
Mistry *et al.* (2021)	Entry: 1.1 mm Apex: 1.9 mm Angle: 6.4°	Entry: 0.4 mm Apex: 0.4 mm Angle: 0.8°

The enhanced precision observed between the 3D-planned and actual implant placements in this investigation for both FH and FG methods can be attributed to various contributing factors, such as the utilization of stereolithographic models instead of real patient cases, application of the advanced R2 Gate® FG protocol, implant parameters like shape, width, and length, operator expertise, and the use of a tooth-supported surgical guide. Findings revealed that FH placement accuracy remained clinically acceptable, offering a reasonable alternative to FG surgery; however, the angular deviation recorded for the FH method in Case 2 (9.12°) could have caused lingual cortex perforation, posing a potential threat to adjacent vital structures [34]. In contrast, FG in the same case decreased the angular deviation to 0.97°, significantly reducing this risk. A comparable pattern was observed in Case 5, where deviation dropped from 11.7° to 0.97°.

Overall, FG surgery exhibited smaller mean deviations between planned and actual implant positions compared to FH, as expected since FH relies more heavily on anatomical reference points and subjective judgment. Notably, in two cases, implants placed using FG were marginally (0.21 mm and 0.25 mm) closer to the IAN than the planned position. The smaller 3D deviations in this study, relative to previous reports, may be due to the use of tooth-supported guides in a bounded saddle configuration, enhancing stability and positional control versus single-saddle or mucosa-supported designs, such as those employed by Vercruyssen *et al.* [32].

Future efforts should emphasize the control of angular deviation during implant insertion to avoid contact with critical structures such as the sinus floor, roots of neighboring teeth, the mandibular nerve, and the anterior loop of the IAN. In one case of this study, FH surgery almost perforated the lingual cortex due to a 9.121° deviation, potentially endangering the lingual artery and risking severe hemorrhage [35]. Conversely, FG reduced the deviation to 0.972°, preventing cortical perforation and minimizing vascular injury risk.

The FG approach's ability to limit angular deviation was further evident in Case 6, where the planned apex position lay lateral to the IAN by only 1.29 mm. Although this setup would not be ethically acceptable for an in vivo study, it was permitted here given the bench-based nature of the experiment. FH placement in this case unexpectedly positioned the apex more medially to the IAN, while FG surgery placed it 0.21 mm closer to the nerve, meaning that, clinically, the drill's 1.5 mm tip extension could have injured the IAN. Such compression might cause a crushing injury to the IAN by pressing against the superior wall of its canal, leading to sensory disturbances [36].

Although rare in implantology, such crushing injuries can be managed or prevented by employing local infiltrations rather than regional inferior dental blocks (IDB). With infiltration anesthesia, the IAN retains pressure sensitivity, allowing the patient to alert the clinician when discomfort arises, prompting immediate cessation of drilling and potential reversal of the implant to relieve pressure, facilitating nerve recovery [37]. Alternatively, depth stops on drills and drivers can help prevent over-penetration and minimize such risks [38].

Limitations of this study included a small number of test cases, the necessity of saline irrigation to prevent overheating and resin deformation during drilling, and possible residual debris that could have interfered with proper implant seating and vertical accuracy—potentially explaining the increased deviation in Case 2 (FG). Moreover, Cases 1, 2, and 6 would not meet in vivo study standards as the planned distances to the IAN were all under 4 mm. In Case 6, both FH and FG techniques placed implants nearer to the IAN than planned, likely causing bony compression and possible nerve injury if performed clinically [39].

Conclusion

Within the limitations of this bench study, both FH and FG techniques demonstrated acceptable accuracy for implant placement near vital structures, provided a 3 mm safety margin is maintained. Nevertheless, FG surgery achieved superior precision, particularly in minimizing angular deviation and controlling implant proximity to the IAN, as evidenced with the R2 Gate® system. Overall, FG appears to deliver enhanced accuracy compared with FH placement. However, clinicians must understand the potential sources of error associated with guide fabrication, 3D printing, and surgical execution, and maintain the skill to transition to FH methods if necessary. Future studies should investigate the operative time, cost-benefit aspects, and reproducibility of FG surgery across larger, multicenter datasets involving multiple operators to better validate and generalize the present findings.

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References

1. Buser D, Arx T. Surgical procedures in partially edentulous patients with ITI implants. Clin Oral Implants Res. 2000;11(1):83–100.
2. Renton T. Prevention of iatrogenic inferior alveolar nerve injuries in relation to dental procedures. Dent Update. 2010;37(5):350–63.
3. Yilmaz Z, Ucer C, Scher E, Suzuki J, Renton T. A survey of the opinion and experience of UK dentists. Implant Dent. 2016;25(5):638–45.
4. Lin CC, Wu CZ, Huang MS, Huang CF, Cheng HC, Wang DP. Fully digital workflow for planning static guided implant surgery: a prospective accuracy study. J Clin Med. 2020;9(4):980.
5. De Angelis P, Manicone PF, De De Angelis S, Grippaudo C, Gasparini G, Liguori MG, et al. Patient and operator centered outcomes in implant dentistry: comparison between fully digital and conventional workflow for single crown and three-unit fixed-bridge. Materials (Basel). 2020;13(12):2781.
6. Walker-Finch K, Ucer C. Five-year survival rates for implants placed using digitally-designed static surgical guides: a systematic review. Br J Oral Maxillofac Surg. 2020;58(3):268–76.
7. Monje A, Insua A, Wang HL. Understanding peri-implantitis as a plaque-associated and site-specific entity: on the local predisposing factors. J Clin Med. 2019;8(3):279.
8. Pauwels R, Jacobs R, Singer S, Mupparapu M. CBCT-based bone quality assessment: are Hounsfield units applicable? Dentomaxillofac Radiol. 2015;44(1):20140238.
9. Beuer F, Schweiger J, Edelhoff D. Digital dentistry: an overview of recent developments for CAD/CAM generated restorations. Br Dent J. 2008;204(9):505–11.
10. Van Noort R. The future of dental devices is digital. Dent Mater. 2012;28(1):3–12.
11. Greenstein G, Tarnow D. The mental foramen and nerve: clinical and anatomical factors related to dental implant placement: a literature review. J Periodontol. 2006;77(12):1933–43.
12. Wareing J, Singh N, Jaffa N, Yankova Z, Cox B, McCaul J. The role of CBCT in OMFS practice.

Br J Oral Maxillofac Surg. 2016;54(Suppl 1):e93–4.

13. Nowak R, Zawiślak E, Batycki J. Factors affecting injury of lingual and inferior alveolar nerve during third lower molar surgery in the mandible. Dent Med Probl. 2014;51(2):225–30.
14. Eggert FM, Levin L. Biology of teeth and implants: the external environment, biology of structures, and clinical aspects. Quintessence Int. 2018;49(4):301–12.
15. McAllister P, Watson M, Burke E. A cost-effective, in-house, positioning and cutting guide system for orthognathic surgery. J Maxillofac Oral Surg. 2017;17(1):112–4.
16. Parnia F, Yazdani J, Javaherzadeh V, Dizaj SM. Overview of nanoparticle coating of dental implants for enhanced osseointegration and antimicrobial purposes. J Pharm Pharm Sci. 2017;20(1):148–60.
17. Tarnow D, Cho SC, Wallace S. The effect of inter-implant distance on the height of inter-implant bone crest. J Periodontol. 2000;71(4):546–9.
18. Grunder U, Gracis S, Capelli M. Influence of the 3-D bone-to-implant relationship on esthetics. Int J Periodontics Restor Dent. 2005;25(2):113–9.
19. Burke R, Richardsen A. Increasing occupational health and safety in workplaces. In: Increasing Occupational Health and Safety in Workplaces. Cheltenham: Edward Elgar Publishing; 2019.
20. Smitkarn P, Subbalekha K, Mattheos N, Pimkhaokham A. The accuracy of single-tooth implants placed using fully digital-guided surgery and freehand implant surgery. J Clin Periodontol. 2019;46(9):949–57.
21. Jacobs R, Salmon B, Codari M, Hassan B, Bornstein MM. Cone beam computed tomography in implant dentistry: recommendations for clinical use. BMC Oral Health. 2018;18(1):117.
22. Jang D, Son K, Lee KB. A comparative study of the fitness and trueness of a three-unit fixed dental prosthesis fabricated using two digital workflows. Appl Sci (Basel). 2019;9(13):2778.
23. Kim SM, Son K, Kim DY, Lee KB. Digital evaluation of the accuracy of computer-guided dental implant placement: an in vitro study. Appl Sci (Basel). 2019;9(16):3373.
24. Huang L, Zhang X, Mo A. A retrospective study on the transferring accuracy of a fully guided digital template in the anterior zone. Materials (Basel). 2021;14(16):4631.
25. Kühl S, Zürcher S, Mahid T, Müller-Gerbl M, Filippi A, Cattin P. Accuracy of full guided vs. half-guided implant surgery. Clin Oral Implants Res. 2012;24(9):941–8.
26. Scherer U, Stoetzer M, Ruecker M, Gellrich NC, Von See C. Template-guided vs. non-guided drilling in site preparation of dental implants. Clin Oral Investig. 2015;19(6):1339–46.
27. Gluckman H, Du Toit J, Salama M. Guided bone regeneration of a fenestration complication at immediate implant placement simultaneous to the socket-shield technique. Int Dent J. 2015;5(2):58–66.
28. Davidowitz G, Kotick PG. The use of CAD/CAM in dentistry. Dent Clin North Am. 2011;55(3):559–70.
29. Tahmaseb A, Wu V, Wismeijer D, Coucke W, Evans C. The accuracy of static computer-aided implant surgery: a systematic review and meta-analysis. Clin Oral Implants Res. 2018;29(Suppl 16):416–35.
30. Fürhauser R, Mailath-Pokorny G, Haas R, Busenlechner D, Watzek G, Pommer B. Esthetics of flapless single-tooth implants in the anterior maxilla using guided surgery: association of three-dimensional accuracy and pink esthetic score. Clin Implant Dent Relat Res. 2015;17(5):e427–33.
31. Schnutenhaus S, Edelmann C, Rudolph H, Luthardt RG. Retrospective study to determine the accuracy of template-guided implant placement using a novel nonradiologic evaluation method. Oral Surg Oral Med Oral Pathol Oral Radiol. 2016;121(6):e72–9.
32. Vercruyssen M, Coucke W, Naert I, Jacobs R, Teughels W, Quirynen M. Depth and lateral deviations in guided implant surgery: an RCT comparing guided surgery with mental navigation or the use of a pilot-drill template. Clin Oral Implants Res. 2014;26(11):1315–20.
33. Younes F, Cosyn J, De Bruyckere T, Cleymaet R, Bouckaert E, Eghbali A. A randomized controlled study on the accuracy of free-handed, pilot-drill guided and fully guided implant surgery in partially edentulous patients. J Clin Periodontol. 2018;45(6):721–32.
34. Baab DA, Ammons WF, Selipsky H. Blood loss during periodontal flap surgery. J Periodontol. 1977;48(11):693–8.
35. Vasconcelos JDA, Avila GB, Ribeiro JC, Dias SC, Pereira LJ. Inferior alveolar nerve transposition with involvement of the mental foramen for implant placement. Med Oral Patol Oral Cir Bucal. 2008;13(12):E722–5.
36. Garcés MAS, Escoda-Francolí J, Gay-Escoda C. Implant complications. In: Implant Dentistry—

The Most Promising Discipline of Dentistry. London: IntechOpen; 2011.

37. Hegedus F, Diecidue RJ. Trigeminal nerve injuries after mandibular implant placement—practical knowledge for clinicians. Int J Oral Maxillofac Implants. 2006;21(1):111–6.
38. Vercruyssen M, Laleman I, Jacobs R, Quirynen M. Computer-supported implant planning and guided surgery: a narrative review. Clin Oral Implants Res. 2015;26(Suppl 11):69–76.
39. Misch CE, Resnik R. Mandibular nerve neurosensory impairment after dental implant surgery: management and protocol. Implant Dent. 2010;19(5):378–86.