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The manufacturing method and guidance system affects the accuracy of implant placement by inexperienced clinicians: a comparative study

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ABSTRACT

Objectives: This study evaluates the accuracy of dental implant placements performed by inexperienced clinicians with surgical guides manufactured at different orientation (0°, 45°, and 90°) using three systems: Fully-guided (FG), pilot-guided (PG), and freehand (FH). The research aims to determine whether these clinicians can achieve precise implant placements in artificial mandibles.

Methods: Three dentistry students with four years of general clinical experience placed a total of 270 implants in 45 modified mandibular models. Each student placed 30 implants using FG, PG, and FH methods with surgical guide manufactured at 0°, 45°, and 90° angulations. Virtual implant planning was conducted using 3Shape software, and accuracy was evaluated by comparing post-placement scans to baseline plans. Statistical analysis included two-way ANOVA to assess the impact of placement method and printing angulation on the implant deviation angle, followed by Tukey post hoc testing for significant differences.

Results: The findings indicate that the FG system yields the highest accuracy with the minimum angle error of 0.12°, followed by the PG and FH systems. Additionally, 3D-printed surgical guides manufactured at a 0° angulation demonstrated superior placement accuracy compared to those at 45° and 90°.

Conclusions: These results have significant implications for clinical practice and training, suggesting that FG systems are preferable for novice clinicians and that optimal printing orientation enhances implant placement accuracy.

A statement of clinical relevance: This in vitro study highlights the importance of printing orientation in the fabrication of surgical guides, as it significantly affects guide accuracy and implant placement precision. Furthermore, the findings suggest that incorporating surgical guide use into pre-clinical training may enhance the performance of novice clinicians and improve surgical outcomes.

1. Introduction

Implant placement is a complex surgical skill that has predominantly been performed by dental specialists, such as periodontists and oral surgeons [1]. With the increasing popularity of implants as a restorative option and advancements in technology, more general dentists are now performing these procedures [2–4]. There is ongoing concern regarding the accuracy of implant placement by inexperienced general dentists using newer computer aided design/computer aided manufacturing (CAD/CAM) surgical guides, and additional training may be required to ensure optimal outcomes, which may lead to surgical or restorative complications [5,6]. Surgical implant guides can incorporate fully guided techniques where all of the surgical corticotomys are performed or pilot surgical guides which are used for the pilot drill to do the initial osteotomy [7–9]. The use of guided surgery or pilot drill systems can result in improved outcomes for implants with fully guided options yielding better clinical outcomes for inexperienced and experienced clinicians [10–15].

Three-dimensional (3D) printing to manufacture the surgical guides is an accepted clinical practice. Ersoy et al. [16] established that stereolithographic surgical guides can be used dependably for implant placement without the need to raise a surgical flap. “Stereolithography is a laser-driven polymerization process that fabricates an anatomic model and surgical guides” (page 2093, line 11) [17]. The fabrication of a

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precise surgical guide is crucial to achieving successful outcomes for implant placement [7]. There are several factors that can affect the accuracy when 3D printing dental devices with printing orientation being a key concern [18–21]. This particularly applies to implant surgical guides with the critical areas being the intaglio surface that fits on the hard and soft tissues and also the internal cylinder that the surgical sleeve is positioned in [22–27]. It has been shown that three-dimensional printing at different thickness layers and different angulations can affect surgical guides [28,29]. In vitro evaluations of the accuracy of the surgical guides lack clinical relevance with the interaction of the fit of the sleeve to the surgical guide being neglected. A number of these studies evaluate the accuracy of the internal surface of the cylinder that locates the metal sleeve sits in, but do not evaluate how the metal sleeve fits or if this results in deviations of the bur used for the osteotomy [23,25,27]. Attempts have been made with in vitro experiments to given clinical relevance. Choi et al. [30] looked at the effect of different diameters, lengths, and distances from the base of the surgical guide to the implant site. They found that the length of the surgical guide affected implant placement accuracy the most. Evaluations of these individual factors alone do add to the understanding of how implant placement may differ from the planned to the actual placement. There are no studies that combine the parameters of surgical guide printing orientation and the subsequent placement of implants in an in vitro context.

Currently, there is insufficient understanding about how varying printing angulations of surgical guides, in conjunction with different implant guide systems, could impact the accuracy of the final implant placement. This manuscript aims to address the gaps in the literature that encompass the interaction between surgical guide angle manufacturing and actual implant placement. It also looks to investigate the lack of knowledge of the type of implant guided surgery and its effect on accuracy for inexperienced clinicians. The specific objectives of this research project were: To assess implant placement accuracy achieved by inexperienced clinicians using fully guided (FG), pilot guided PG, and free hand (FH) techniques; to evaluate the impact of surgical guide angulation (0°, 45°, and 90°) on implant placement accuracy; and to analyse the predictability of outcomes by examining results across multiple trials conducted by each clinician. The null hypothesis assumed that there would be no significant difference in implant placement accuracy among inexperienced clinicians when comparing the fully guided technique to the PG and FH techniques, regardless of the angulation at which the surgical guides are printed (0°, 45°, and 90°).

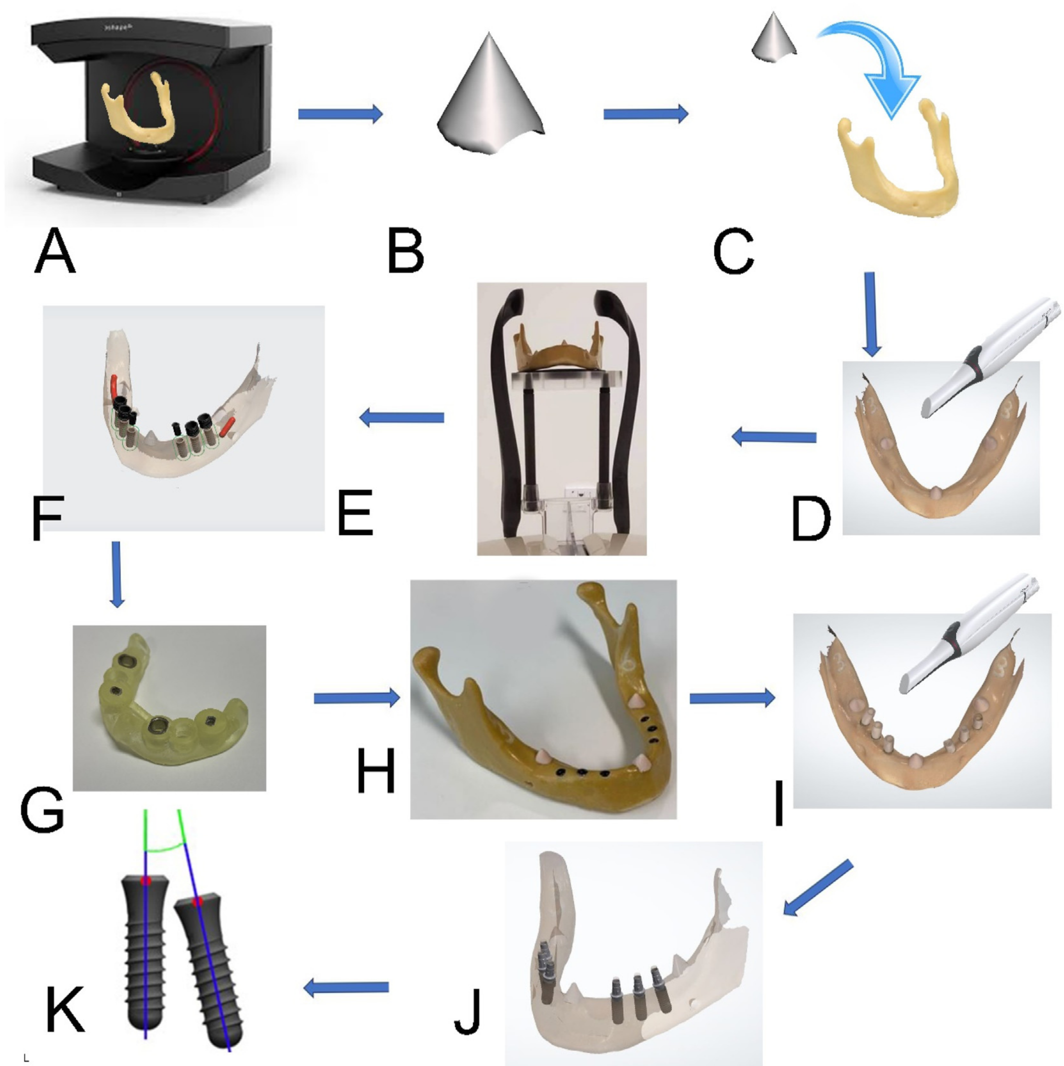

Fig. 1. Graphical method representation: Scan mandible (A), Design and manufacture alignment cones for model (B), Adhere cones to model (C), Scan model (D), acquire CBCT of Model (E), Plan position of implants (F), Manufacture surgical guide (G), Place implants in model (H), Scan model with scan bodies in place (I), Match scan body scan to virtual scan bodied to generate virtual implant position (J), Analyse accuracy of actual versus planned position (K).

2. Materials and methods

2.1. Participants

To test the null hypothesis a total of 270 implants were placed, with three participants placing 90 implants: 6 implants in 15 mandibular models. Each participant placed 30 implants FH, 30 implants using the PG technique, and 30 implants using the FG technique. Within these groups, each participant placed 30 implants using surgical guides printed at a 0° orientation, 30 implants using surgical guides printed at a 45° orientation, and 30 implants using surgical guides printed at a 90° orientation. The participants were three fourth year dentistry students. These students had four years of general dentistry clinical experience but no previous experience with implant placement. As part of their program, they had studied the fundamental theory of implant treatment planning and implant placement.

2.2. Models and surgical guide fabrication

Forty-five fully edentulous mandibular training models (Straumann Pty Ltd., Melbourne, Australia) were used for this study. These models were modified to support standardized surgical guide placement. Initially, each model was scanned using a laboratory scanner (3Shape, Copenhagen, Denmark) to capture high-resolution digital models (Fig. 1A) (see Fig. 2).

Three custom cone-shaped locator structures were designed and digitally positioned at precise anatomical landmarks: the midline, the region corresponding to the third molar in quadrant three, and the third molar in quadrant four (Fig. 1B). These locator cones were printed using an 3D printer (Asiga, NSW, Australia) and adhered to the models using Selleys Araldite Epoxy Resin Paint (DuluxGroup, Victoria, Australia) (Fig. 1C). These structures served to ensure consistent surgical guide positioning across all models.

Following this, each model was scanned using the same intraoral scanner (Trios 4, 3Shape, Copenhagen, Denmark) under strictly controlled and standardized conditions. A consistent scanning strategy was employed: beginning with a continuous lingual scan of the entire arch, followed by a cross-arch stitching scan to complete the buccal and occlusal aspects (Fig. 1D). The same operator performed all scans, in a controlled lab environment, to minimize operator variability. Scanner calibration was performed daily prior to scanning sessions in accordance with manufacturer protocols.

CBCT scans of all models were acquired using the Carestream CS9000 CBCT system (Carestream, Atlanta, USA), maintaining identical settings for each scan to ensure consistency across the sample (Fig. 1E). Exposure parameters and voxel size were kept constant for all scans.

The intraoral and CBCT datasets were imported into Implant Studio software (3Shape, Copenhagen, Denmark) for virtual implant planning (Fig. 1F). Six implants were virtually planned in each model: three in quadrant three (sites 33, 35, and 36) and three in quadrant four (sites 43, 45, and 46). Each quadrant contained one FG, one PG, and one FH implant, with allocation randomized using Research Randomizer software [31].

All implants were 4.1 mm in diameter and 10 mm in length (Straumann Bone Level Implants), placed with a 5 mm inter-implant distance, complying with the manufacturer's safety recommendations. Implant placement was influenced by CBCT-derived model density. Implant data were exported as proprietary .XML files for surgical guide design. Each surgical guide covered the full arch and was uniquely labeled by sample number (Fig. 1G).

A total of 45 surgical guides were printed using the a 3D printer (Asiga Max UV, NSW, Australia) in NextDent SG surgical guide resin (3D Systems). The guides were divided into three groups (n = 15 per group), printed at 0°, 45°, and 90° build orientations respectively (Fig. 3). All guides were post-processed in 91 % isopropyl alcohol, and sleeves were placed and fixed using light-cured resin per manufacturer instructions (NextDent, LC-3DPrint Box). Guides were autoclaved at 121 °C for 30 min, sealed in individual sterilization pouches.

Each guide received four Straumann metal sleeves: two for PG (pilot drill only) and two for FG (full guidance). Sleeves were seated flush with both intaglio and cameo surfaces and verified visually and with reference markings (Fig. 1G).

To minimize placement sequence bias, the FH implants were placed first, followed by PG, and then FG within each quadrant. FH placements followed full manual drilling without a guide. PG placements used the guide for the initial pilot drill only; all subsequent drills were freehand. FG placements were fully guided using the surgical guide for all

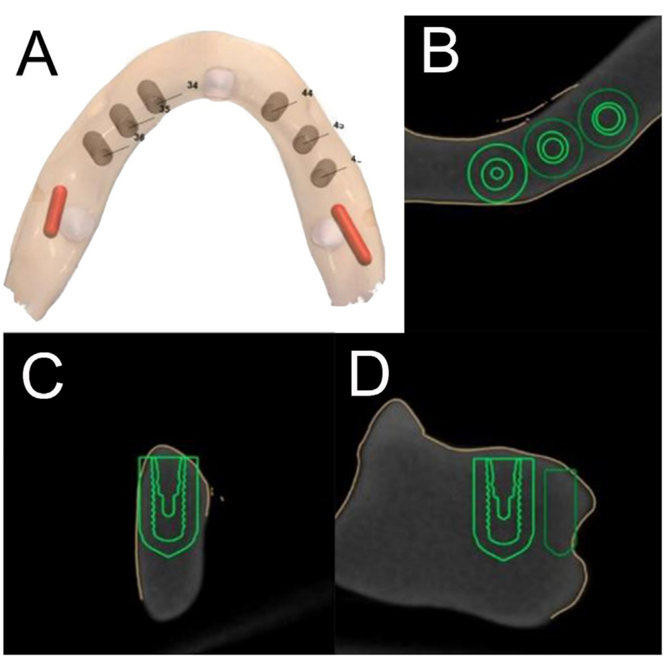

Fig. 2. Visualization of planned implant positions on Implant Studio, 3 Shape Software for (A) Axial view (B) Sagittal view (C) Coronal view (D).

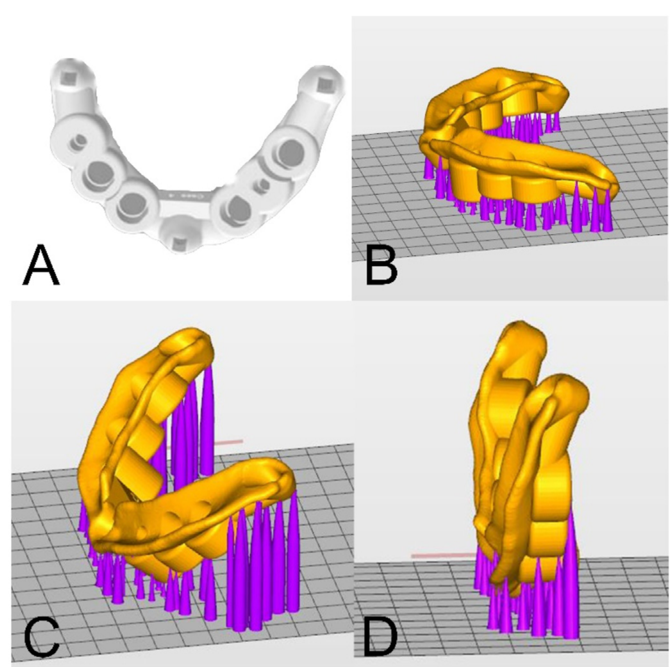

Fig. 3. Designed surgical guide (A), Surgical guide orientated at 0° (B), Surgical guide orientated at 45° (C), Surgical guide orientated at 90° (D).

osteotomy steps and implant placement (Fig. 1H). All implant placements were completed using standard Straumann surgical kits.

2.3. Accuracy evaluation

To evaluate the accuracies of implant placement Straumann scan bodies (CARES RC Mono Scan body D 4.1 mm, H 10 mm) were fixed to each implant in the mandibles (Fig. 1I). The original scan of the model was then copied in the scanning software (Dental Desktop, 3Shape) and the region where the implant was placed deleted. This deleted area, now with the scan body, was then scanned (Trios 4, 3Shape, Copenhaggen, Denmark). This ensures that the orientation of the model is not changed from the planning phase to the data acquisition phase and that a direct comparison of planned and actual implant can be performed. The standard tessellation files of the scans with scan bodies were imported into commercial dental designing software (Dental Designer, 3Shape). The virtual scan bodies are aligned to the scan. This produces a virtual representation of where the actual implant was placed which is exported as a .XML file (Fig. 1J). The original (obtained at the implant planning phase) and actual .XML file representing the planned and placed implant positioned is then imported to a proprietary the 3Shape Implant Placement Comparer Tool. This calculates the error angle (°) for each implant (Fig. 1K). The error angle is a parameter that is defined as the angulation deviation created when an angulation measurement is made between virtual long axis line of the actual implant placement and planned implant placement a graphical representation can be seen in Fig. 1K. This will be referred to as the implant angle deviation (IAD).

2.4. Statistics

Statistical analyses were performed using statistical package for the social sciences (SPSS) software (Windows Version 23, SPSS Inc.) A two-way analysis of variance (ANOVA) was employed to examine the impact of placement method and angulation level on the IAD predefined significance level of .05. The first independent variable, placement method, was classified into PG, FH, and FG. The second independent variable, angulation, included 0°, 45°, and 90°. The measured dependent variable was the IAD of the planned versus actual implant position. Descriptive statistics of mean and standard deviation were calculated for each variable. Efforts were made to maintain relatively balanced group sizes to strengthen the ANOVA model and avoid violating its assumptions. The Levene test was conducted to assess the homogeneity of variances. In cases of significant differences, the Tukey post hoc test was used.

3. Results

The means and standard deviations for the IAD are presented in Table 1 for each placement group at each level of angulation. The initial dataset comprised 270 observations. Subsequently, seven instances were excluded due to IAD lying beyond the acceptable range. No implausible values were identified across the three variables. The dataset remained complete, with a final count of 263 observations. The mean scores of IAD are lowest in the FG placement method across all levels of angulation. However, there is not a significant difference in the mean scores between the FH and PG placement methods. The maximum IAD was 25.58° for the FH placement method, with higher variance also noted in this method. Conversely, the FG placement method exhibited the minimum angle error of .12° with the lowest variance. The Levene test for homogeneity of variances was not statistically significant, f(8, 255) = .803, p = .600, indicating that the assumption of homogeneity of variance was met. The angulation levels are independent, and each experimental placement method was drawn independently as well, ensuring sample independence. The dependent variable was normally distributed for each group, with similar numbers of observations in each group.

The results indicate a significant main effect for placement method on IAD, F (2, 252) = 21.57, $p < .001$, with a partial η^2 of .146, indicating a large effect size. Conversely, there was a non-significant main effect for angulation level on IAD, F (2, 252) = 2.69, $p > .05$, with a partial η^2 of .021, suggesting a small effect size. Additionally, there was a non-significant interaction between placement method and angulation level on IAD, F (4, 252) = .986, $p > 0.05$, with a partial η^2 of .015, also indicating a small effect size. Post hoc analysis using Tukey's honest significance test indicated that the IAD were significantly lower for the FG placement method compared to both the FH (mean difference of 5°) and PG (mean difference of 4°) methods (p = .001). However, there was no significant difference between the FH and PG methods (mean difference of just 1°) (p = .17). The 95 % confidence interval in Table 2 shows the range of possible values for the difference between the FG and FH methods to be between 3.63 and 6.98, and between the FG and PG methods to be between 2.46 and 5.81. The profile plot, displayed with 95 % confidence limits for each of the placement groups, clearly illustrates that the mean scores for the IAD are lowest in the FG placement method (Fig. 4).

Table 1
Mean and Standard Deviation of implant angle deviation for placement groups at different angulations.

	Mean (Standard deviation)	Minimum	Maximum	N
Angulation 0				
FG (A)	5.14 (4.70)	.19	14.20	29
FH (B)	8.60 (5.17)	.94	19.24	29
PG (C)	8.98 (5.62)	.77	20.26	30
Angulation 45				
FG (A)	6.45 (5.08)	.12	17.26	28
FH (B)	11.96 (6.24)	1.37	25.58	28
PG (C)	9.59 (5.62)	1.38	19.27	27
Angulation 90				
FG (A)	5.10 (4.57)	.258	17.47	30
FH (B)	12.03 (6.65)	1.53	24.67	30
PG (C)	10.51 (6.29)	.69	21.42	30

FG = fully-guided; FH = freehand; PG = pilot-guided.

4. Discussion

The study aimed to investigate whether inexperienced clinicians could accurately place implants using FH, PG, and FG implant systems and conversely having the outcome of determining if the printing orientation of surgical does effect the accuracy of implant placement. It was hypothesized that the FG implant system would allow novice clinicians to achieve the most accurate placements in artificial mandibles, followed by PG and FH methods. The outcome of this study supported the hypothesis, indicating that the FG implant system facilitated the most accurate placements by inexperienced clinicians in artificial mandibles. This finding was consistent with previous studies, such as Abduo & Lau [31], which also analysed the accuracy of implant placement using these three systems. The multiple trials conducted by each clinician to obtain mean values further substantiated the hypothesis.

The results of this study revealed that implants were more accurately placed when using surgical guides 3D printed at a 0° angulation, exhibiting the lowest mean IAD. The use of inexperienced clinicians gives these findings greater weight as any previous experience with surgical guides or implant placement may have influenced the results and therefore does do not need to be mitigated. The mean values between the surgical guides 3D printed at 45° and 90° angulation showed no significant difference when comparing PG and FG systems. Similarly, there was no significant difference in mean values for FH placement in these groups, perhaps indicating that any steep angulations during 3D printing may have a detrimental effect on the fit of the surgical guide to the model or the fit of the metal sleeve to the surgical guide itself.

This substantiates and aligns with previous in vitro studies investigating the accuracy of the actual geometry of the manufactured surgical guides that indicate printing at 0° and lower angulations improve the quality of the internal surfaces of the metal sleeve cylinder resulting in

Table 2
Pairwise comparisons of error angle different surgical guide techniques and surgical guide manufacturing orientations.

Angle of surgical guide manufacture	(I) Placement Method	(J) Placement Method	Mean Difference (I-J)	Std. Error	Sig.[b]	95 % Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
0°	Free Hand	Fully Guided	3.469*	1.471	.019	.572	6.366
		Pilot Guided	−.379	1.459	.795	−3.252	2.494
	Fully Guided	Free Hand	−3.469*	1.471	.019	−6.366	−.572
		Pilot Guided	−3.848*	1.459	.009	−6.721	−.975
	Pilot Guided	Free Hand	.379	1.459	.795	−2.494	3.252
		Fully Guided	3.848*	1.459	.009	.975	6.721
45°	Free Hand	Fully Guided	5.503*	1.511	.000	2.527	8.478
		Pilot Guided	2.524	1.498	.093	−.427	5.474
	Fully Guided	Free Hand	−5.503*	1.511	.000	−8.478	−2.527
		Pilot Guided	−2.979*	1.484	.046	−5.902	−.056
	Pilot Guided	Free Hand	−2.524	1.498	.093	−5.474	.427
		Fully Guided	2.979*	1.484	.046	.056	5.902
90°	Free Hand	Fully Guided	6.754*	1.459	.000	3.881	9.627
		Pilot Guided	1.340	1.459	.359	−1.533	4.212
	Fully Guided	Free Hand	−6.754*	1.459	.000	−9.627	−3.881
		Pilot Guided	−5.415*	1.446	.000	−8.263	−2.566
	Pilot Guided	Free Hand	−1.340	1.459	.359	−4.212	1.533
		Fully Guided	5.415*	1.446	.000	2.566	8.263

Based on estimated marginal means *. The mean difference is significant at the .05 level.
Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).
The Levene test on homogeneity of variances is not statistically significant, $F(8, 255) = .803$, $p = 0.600$.

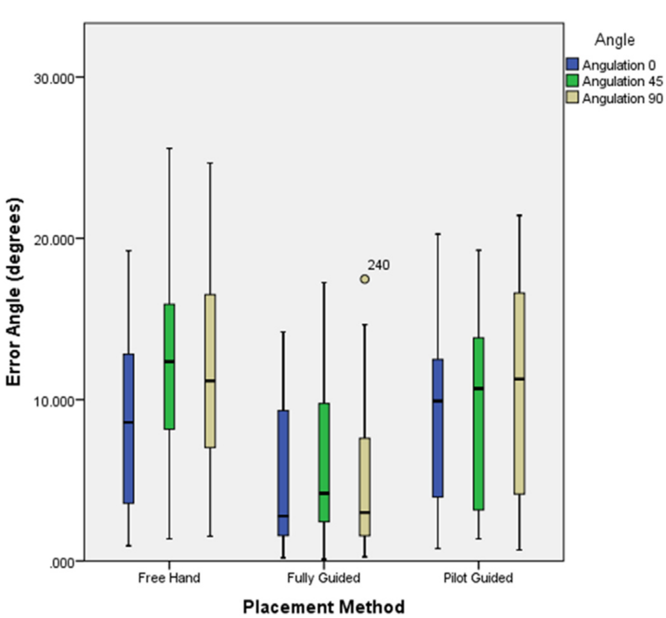

Fig. 4. Box Plot for fully-guided (FG), freehand (FH), and pilot-guided (PG) placement methods at different printing orientations comparison to 95 % Cl Error Angle (degrees).

improved fit [24–27]. Additionally, when assembling, the guide sleeves were a better fit in the 0° printed guides. Revilla-León et al. [32] investigated the printing orientations of occlusal dental devices and concluded that those printed at 0° showed the best manufacturing accuracy values, coinciding with commercial manufacturer recommendations. They observed a trend indicating that higher print orientations resulted in greater deviations from manufacturing trueness. This finding is further supported by Tahir & Abduo [33], who implied that guides printed parallel to the printed platform, or at 0°, allow for the least deviation in implant placement. However, guides printed at a 45° angle have limitations. Since these guides were not printed horizontally or at a perpendicular axis, inaccuracies could form on the internal surface of the cylinders during. Inaccuracies in the cylinder the sleeves fit into, in the surgical guides, can affect the affect the placement of the implant. Ali et al. [34] further support this finding by demonstrating that there were more deviations in parallelism between cylinders in guides printed at 45°. Therefore, printing orientation is clinically significant when using surgical guides to ensure the best implant placement. Clinicians and dental laboratories should consider manufacturing surgical guides at lower printing orientations. Issues with final implant placement in clinical contexts should critically evaluate if this is a factor. The results of this invitro study build on this demonstrating that this translates to higher levels of congruence between the planned and actual implant position.

Based on the findings of the current study utilizing a FG implant system emerges as the preferred method for implant placement in clinical practice, particularly for inexperienced clinicians. Consequently, inexperienced clinicians should be capable of placing implants as proficiently as experienced clinicians by employing FG implant system. Surgical guides should ideally be printed at a 0° angle to optimize the accuracy of implant placement. The practical clinical implications of this research suggest that FG implant systems have the potential to become the gold standard in clinical practice. As implants gain popularity as a treatment option for missing dentition due to aesthetics, the results imply that even graduate dentists can confidently perform implant procedures and expand their scope of practice if a surgical guide is used when considering the position of the implant [35–37].

The findings of this study are consistent with several previous in vitro investigations examining the accuracy of 3D-printed surgical guides. Specifically, it corroborates reports that printing at 0° or lower angulations enhances the internal surface quality of metal sleeve cylinders, resulting in better sleeve fit and improved implant placement accuracy [24–27]. This was evident during assembly, where guide sleeves exhibited superior congruence in guides printed at 0°. Revilla-León et al. [33] similarly reported that occlusal devices printed at 0° demonstrated the highest manufacturing accuracy, aligning with manufacturer recommendations. Their study observed that deviations from trueness increased at higher print orientations, a trend echoed in the current findings. Further supporting this, Tahir & Abduo [34] emphasized that guides printed parallel to the build platform (0°) yield minimal deviation in implant placement. Conversely, guides printed at 45° were found to be less reliable. The present study reinforces this, noting that printing surgical guides at 45° introduced inaccuracies on the internal surfaces of the sleeve cylinders, potentially compromising the seating of the guide sleeve and thus implant positioning.

Our findings are further substantiated by more recent studies. Salazar Rios et al. [43] demonstrated that surgical guides printed at 0° exhibited superior accuracy in intaglio surface detail and overall fit compared to those printed at steeper angles. Similarly, Ali et al. [44] found that guides printed at 45° showed greater deviations in cylinder parallelism and internal fit, echoing our observation that higher printing angles compromise precision. Alghauli et al. [45], in a systematic review and meta-analysis, confirmed that 0° orientation consistently yielded the best outcomes across various dental devices, emphasizing the clinical relevance of this parameter. Additionally, this study highlights those inaccuracies in the internal cylinder surface—more pronounced in guides printed at 45°—can directly affect the seating of the sleeve and ultimately the accuracy of implant placement. These findings collectively demonstrate that printing orientation is not merely a technical variable, but a clinically significant factor in achieving accurate implant outcomes. The study adds further evidence that this parameter remains significant even when guides are used by inexperienced clinicians, showing higher levels of congruence between the planned and actual implant positions in the 0° printed group. Clinicians and dental laboratories should be encouraged to adopt lower print orientations, and deviations observed clinically should prompt a review of guide fabrication protocols, particularly print orientation.

Moreover, the results suggest that PG implant systems remain beneficial, offering certain advantages over FG systems while maintaining accuracy, as evidenced by a significant improvement over FH placement. PG systems enable the clinician to initiate placement at the planned position with the correct inclination while still allowing observation of anatomical borders and the option to raise a flap if necessary [35]. This is clinically significant, especially when placing implants that are to be joined by the abutment where the angle of insertion of both screws needs to be parallel [38]. Additionally, it is important when placing anterior implants due to a thinner alveolar ridge in these regions. PG systems are also important for anterior single-unit implants but are not as critical for posterior single-unit implants, especially when compared to FH techniques. However, clinicians should be mindful of the disadvantages associated with FG systems. Despite higher survival and clinical success rates, factors such as cost and restricted interocclusal space suggest that FG systems may not be the benchmark in all cases [39]. Furthermore, any defects or corrections to bone are challenging to address since the FG system is minimally invasive and does not raise a flap [40].

The focus of previous invitro studies investigating the accuracy of surgical guides from the perspective of manufacturing parameters [20], fit of the sleeves in the surgical guide [41], or the effect of autoclaving the surgical guides are important for an understanding of the process [9]. However, investigating these parameters separately oversimplifies the process and may not actually determine the ultimate end goal which is accurate implant placement aided by a surgical guide [8]. Previous in vitro investigations do assess the cylinder that the implant guide sleeves are positioned in, however omit the critical step of assessing how the surgical guide sleeve fits in the surgical guide, which ultimately dictates the corticotomy and implant placement [27]. This represents a methodological flaw for this in vitro study and could be address in future study by assessing the position of the digitally planned surgical sleeve with the actual surgical sleeve post manufacturing. The effect of autoclaving on the dimensional accuracy may also effect surgical guide and this implant position [9]. However this invitro study again is not able to directly link the variable of autoclaving with the actual implant placement thus leaving the authors to speculate that this would affect the final outcome of implant placement. This demonstrates that in vitro experiments need to draw direct links to implant placement in order for the data to translate to in vivo investigations, as seen in this investigation.

This research had several limitations that could have influenced the resulting data. Firstly, the implants were strategically planned to be placed in three different regions of the mandible to simulate anterior, premolar, and molar-positioned implants. However, it became evident during placement that placing some implants in the anterior region of the mandible proved difficult due to the narrowness of the "alveolar bone" on the artificial mandibles. This challenge was particularly pronounced when using the PG and FH systems, leading to implants being placed too labially and resulting in perforations. Moreover, this procedure was comparatively easier than placing implants in a patient, where the operator would have to contend with limitations in mouth opening, interarch clearance, as well as blood, soft tissue, and saliva [31]. The number of participants, three clinicians, also limited the study outcomes but the large sample size helped to overcome this. Including clinicians with intermediate and advanced levels of experience would have also improved the outcomes of this study. The surgical guides could have been manufactured at a greater number of angles, particularly at lower angles such as 15° or 30° to investigate if there is a lineal improvement in implant placement accuracy. Multiple 3D printers could have been utilised to determine if the 3D printing apparatus had an effect on the accuracy of the surgical guide and consequently the implant placement. These factors were limited by the number of consumables available to the study.

Whilst this investigation builds upon previous research on inexperienced clinician skills, implant systems, and the printing angulation of surgical guides, future studies are needed to delve further into these areas. Previous inquiries have explored variations of the current research, including the use of mannequin heads, artificial maxilla's or cadaver jaws, and partially edentulous jaws. Subsequent studies could investigate the time taken to place implants using the three implant systems, as previous studies have primarily compared the timing using PG and FG system [10]. Schulz et al. [42] also found perforations of the buccal and lingual wall where implants were placed in areas where the alveolar ridge was thin, despite using a FG system. Furthermore, the implants were placed with the mandible parallel to the floor, rather than at an angle that a patient's head would be in-chair. Using mandibles that mimic the clinical scenario more closely, such as partially edentulous mandibles or placing the mandibles in a phantom head could give greater clinical relevance.

5. Conclusions

This in vitro study attempts to bridge the gap between accuracy studies for surgical guides and their effect on implant placement. The following conclusion can be drawn:

- Inexperienced users can benefit from the fully guided approach of implant placement with surgical guides.
- Preclinical education for clinician training in implant procedures could benefit from implementing the experimental method presented in this manuscript to familiarize with different implant placements methods.
- Surgical guides manufactured at angles of 0°, as opposed to 45° or 90° produce optimal results when pertaining to the actual implant placement.

CRediT authorship contribution statement

Hannah Dhaliwal: Writing – review & editing, Software, Investigation, Formal analysis, Data curation. **Alyssa Margolian:** Software, Investigation, Formal analysis, Data curation. **Selina Tran:** Validation, Software, Methodology, Investigation, Data curation. **Andrew B. Cameron:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Funding acquisition, Conceptualization. **Lavanya Ajay Sharma:** Writing – original draft, Validation, Supervision, Project administration, Methodology, Conceptualization. **Ajay Sharma:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

Data availability statement

Data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Ethics statement

The present study protocol was reviewed and approved by the ethics committee of the Griffith University Research Ethics Manual (GUREM).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests Ajay Sharma reports equipment, drugs, or supplies was provided by Straumann Holding AG. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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