Received: 29 March 2021 | Revised: 15 May 2022 | Accepted: 24 June 2022
DOI: 10.1111/clr.13981

ORIGINAL ARTICLE

CLINICAL ORAL IMPLANTS RESEARCH WILEY

Accuracy of a chairside, fused deposition modeling three-dimensional-printed, single tooth surgical guide for implant placement: A randomized controlled clinical trial

Yao Sun[1,2] | Qian Ding[1] | Fusong Yuan[3] | Lei Zhang[1] | Yuchun Sun[3] | Qiufei Xie[1]

[1]Department of Prosthodontics, Peking University School and Hospital of Stomatology, Beijing, China

[2]Department of Prosthodontics, The Third Clinic of Peking University School and Hospital of Stomatology, Beijing, China

[3]Faculty of Prosthodontics, Center of Digital Dentistry, Peking University School and Hospital of Stomatology & National Engineering Laboratory for Digital and Material Technology of Stomatology & Research Center of Engineering and Technology for Digital Dentistry of Ministry of Health, Beijing, China

Correspondence
Lei Zhang, Department of Prosthodontics, Peking University School and Hospital of Stomatology, 22 South Street ZhongGuanCun, Haidian District, Beijing 100081, China.
Email: drzhanglei@yeah.net

Yuchun Sun, Center of Digital Dentistry, Peking University School and Hospital of Stomatology, 22 South Street ZhongGuanCun, Haidian District, Beijing 100081, China.
Email: polarshining@163.com

Funding information
The Beijing Natural Science Foundation, Grant/Award Number: 7192233; The Beijing Municipal Science and Technology Commission Research Fund, Grant/Award Number: Z161100000116092; The Capital's Funds for Health Improvement and Research, Grant/Award Number: 2020-2-4104

Abstract

Purpose: To compare the accuracy of chairside, fused deposition modeling (FDM) three-dimensional (3D)-printed surgical guides with that of stereolithographic guides for implant placement in single edentulous sites within a clinical setting.

Materials and Methods: A total of 28 participants with 30 single posterior edentulous sites were included. The sites were randomized into a FDM 3D-printed surgical guide group (test) or stereolithographic guide group (control) of equal size ($n = 15$). In both groups, digital implant planning was performed using data from cone beam-computed tomography and intraoral scans. The test group's surgical guides were fabricated using a chairside, FDM 3D-printer; those in the control group were fabricated using a light-curing 3D-printer. Postoperative intraoral scans were used to obtain the 3D position of the implants. Compared to preoperative design, the angular, 3D, mesiodistal, buccolingual and apicocoronal deviations at the implant shoulder and apex were recorded.

Results: The workflow for the design and chairside fabrication of implant guides was established. The mean angular deviations of the test and control group were (4.23 ± 2.38) ° and (4.13 ± 2.42) ° ($p > .05$), respectively. The respective 3D deviations at the implant shoulder were (0.70 ± 0.44) mm and (0.55 ± 0.27) mm ($p > .05$); those at the implant apex were (1.25 ± 0.61) mm and (1.11 ± 0.54) mm ($p > .05$). The mesiodistal, buccolingual, and apicocoronal deviations at the implant shoulder and apex did not significantly differ between the groups ($p > .05$).

Conclusions: Implants for single posterior edentulous spaces were placed as accurately with the test guide as with the control. Further research under more complex situations involving multiple missing teeth is needed.

KEYWORDS
accuracy, dental implant, fused deposition modeling 3D printing, stereolithography, surgical guide

1 | INTRODUCTION

In recent years, the accuracy of implant placement has received much attention under the guidance of the 'prosthetically driven' implant treatment concept (Garber & Belser, 1995). Conventional, non-guided, implant surgery is highly dependent on the practitioner's experience and skill. With the development of computer-aided design/computer-aided manufacturing technology and cone beam-computed tomography (CBCT), digital technology is being used increasingly extensively to assist implant surgery (Jung et al., 2009; Van Assche et al., 2012; Vercruyssen, Fortin, et al., 2014; Vercruyssen, Hultin, et al., 2014). A commonly used example is digital surgical guides, which offer high predictability (D'Haese et al., 2017; Hultin et al., 2012).

For years, surgical guides were fabricated in large commercial laboratories, which involved offsite transportation of models meeting certain design specifications (Deeb et al., 2017; Whitley et al., 2017). The manipulation process is traditionally time-consuming and expensive, with little scope for automation, making it unsuitable for chairside use in terms of efficiency and cost. Meanwhile, stereolithography (SLA)—a type of 3D printing technology—is widely used to fabricate surgical guides (D'Haese et al., 2017). During the SLA process, photosensitive polymer is cured using a focused ultraviolet light layer by layer in a vat of liquid polymer with high speed and precision. After 3D printing is completed, the post-processing is carried out involving post-polymerization in a UV oven and removal of the supports. However, SLA is costly compared with other rapid prototyping techniques (Alharbi et al., 2017; Dawood et al., 2015; Ligon et al., 2017; Torabi et al., 2015). In addition, the uncured 3D printing resin can cause skin sensitization through contact and irritation through inhalation (Dawood et al., 2015), limiting its chairside applicability.

Fused deposition modeling (FDM) is an efficient 3D-printing technology with low costs and appropriate precision for medical use (Boursier et al., 2018; Calcagnile et al., 2018; Chen et al., 2016). During the FDM process, thermoplastic material is extruded from the printer nozzle and a 3D structure is accumulated layer by layer. Printing is then completed with removal of the support structures. When printing small-scale objects, such as surgical guides with three to four teeth spans for a single missing tooth, the printing speed and efficiency are higher with FDM than SLA. However, when printing objects with a relatively large volume, such as guides aimed at a large span or objects requiring mass production, FDM is less effective. Overall, the cost of equipment and respective materials are lower with FDM than with SLA. With FDM, one of the most commonly used materials is polylactic acid (PLA), a low-cost biocompatible polymer extracted from corn that can be used in various biomedical applications (Ligon et al., 2017; Madhavan et al., 2010; Molinero-Mourelle et al., 2018). However, the accuracy of FDM is reported to be lower than that of SLA (approximately 100~150 versus 25~100 μm, respectively) (Ligon et al., 2017). Our research group independently developed a chairside, FDM 3D printer for clinical use (Figure 1) (Yuan et al., 2019). Implant placement using a chairside, FDM 3D-printed surgical guide exhibited a similar accuracy to that obtained with a stereolithographic guide (Pieralli et al., 2020; Sun et al., 2019), and could improve efficiency in an in vitro study (Sun et al., 2019). However, FDM 3D printing of surgical guides in a clinical setting has yet to be reported.

This randomized controlled trial aimed to evaluate the accuracy of implant placement with a chairside, FDM 3D-printed surgical guide, compared with the more frequently used stereolithographic guide. The null hypothesis was that there would be no significant difference between these two types of surgical guide in terms of transfer accuracy.

2 | MATERIAL AND METHODS

2.1 | Study participants

The study was registered with the Chinese Clinical Trial Registry and the World Health Organization (ChiCTR1800015621), and followed the CONSORT 2010 statements (https://www.consort-statement.org/consort-2010). Ethical approval was obtained from the Peking University School of Stomatology Biomedical Institutional Review Board (No. PKUSSIRB-201628055). This study was conducted in accordance with the tenets of the Declaration of Helsinki and the guidelines of Good Clinical Practice. Participants were consecutively recruited from partially edentulous patients who received implant surgeries in the posterior region.

Patients were eligible for inclusion if they were aged over 18 years with no contraindications for implant treatment; had good periodontal health; had a single tooth missing for over 3 months in each posterior region; had greater than a 6 mm mesiodistal edentulous space; did not need bone augmentation; and had proper treatment compliance.

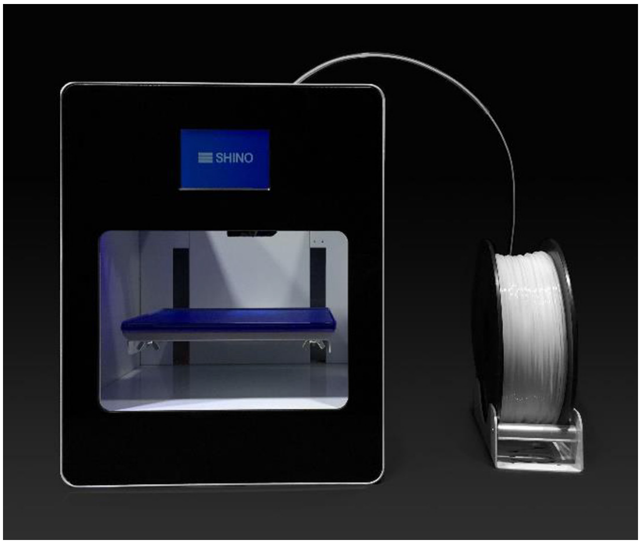

FIGURE 1 Chairside, FDM, 3D printer (Lingtong III, BeijingSHINO, China)

Patients were excluded if they had psychological/mental disorders; had a limited mouth opening that precluded the handpiece from being putin when the guide was in place; had uncontrolled periodontal disease; had endodontic disease of adjacent teeth; were pregnant or breastfeeding women; smoked more than 10 cigarettes daily; or suffered from other general contraindications for implant treatment.

This randomized controlled trial compared chairside FDM 3D-printed surgical guides (the test group) with stereolithographic guides (the control group). The included patients were randomly allocated using computer-generated random numbers, and an envelope technique was used to hide the grouping. A researcher not involved in the study performed the randomized allocation, and the principal researcher enrolled and allocated all study patients to intervention. Only after the patients were enrolled would the researchers know the group assignments, thus avoiding any selection bias. A fully blinded study was not applicable due to the trial design. All patients were informed about the study methods and signed written informed consent. All surgeries were performed by one prosthodontist at the Department of Prosthodontics, Peking University School and Hospital of Stomatology, Beijing, China, between January 2018 and February 2019.

Sample size calculation was based on non-inferior assumptions. We considered a difference of 2° in mean angular deviation as being of clinical significance; therefore, the difference between the test and control groups was considered significant if their mean angular deviation differed by at least 2°. Based on a significance level of 0.025 and power of 80%, the sample size was calculated to be 12 per group. Considering a 20% loss rate for follow-up, the sample size was determined to be 15 per group.

2.2 | Intervention

2.2.1 | Data collection

The included patients received clinical (Figure 2) and CBCT examinations (VGi, NewTom, Italy) to get information of the alveolar bone. Digital imaging and communications in medicine (DICOM) data were exported. An intraoral scanner (TRIOS Standard, 3Shape A/S, Copenhagen, Denmark) was used to scan the patients' defect dentition to obtain information of dentition and mucosa. Standard triangle language (STL) data were then exported.

2.2.2 | Implant planning and surgical guide design

The CBCT and intraoral scan data were imported into coDiagnostiX software (coDiagnostiX 9; Dentalwings GmbH, Chemniz, Germany) according to the manufacturer's instruction. The DICOM and STL datasets were matched by point-to-point registration. Based on the quality and quantity of the bone indicated by CT in the edentulous area, Straumann SLA bone-level implants (Straumann AG, Basel, Switzerland) were selected. The optimal implant position was determined according to the center and axis of the simulated crown as well as the standard of conventional implant placement. After choosing the Straumann® Guided Surgery Cassette and T-sleeve (ϕ5 mm), surgical guides resting on the adjacent teeth were designed to guide the implant bed preparation. One adjacent tooth was chosen in the mesial and distal regions, respectively, to support the guide in the test group. One adjacent distal tooth and two adjacent mesial teeth were chosen to support the guide in the control group. The STL data of the designed guides were exported.

2.2.3 | Surgical guide fabrication

Test group: a chairside, FDM 3D-printer (Lingtong III, Beijing SHINO, Beijing, China) using a PLA filament printed the guides with the following parameters: layer thickness, 0.2 mm; nozzle temperature, 200 °C; nozzle diameter, 0.3 mm; deposition speed, 20 mm/s. The STL data of the designed guides were imported into the print-setting software, and the placement angle was adjusted to make the long axis of each guide as close as possible to the y-axis. Then the data were imported into the printer, and the printer automatically printed the unsupported PLA guides. Subsequent adjustment and polishing, and placing of the sleeve (5 mm, T-Sleeves, Article 034.053v4, Straumann) completed the guides. Each guide was then tried in the patient's mouth to check its position and retention (Figure 3a).

Control group: the guide fabrication was outsourced to the dental lab. The design data were transferred to a dental laboratory, where an SLA 3D printer (Objet30 Pro, Stratasys Ltd, Rehovot, Israel) using a kind of photopolymer (VeroClear, Stratasys Ltd, Israel) was used to print the guides with a layer thickness of 0.016 mm and accuracy of 0.1 mm. Patients needed a second visit to try the guide and check its position and retention (Figure 3b).

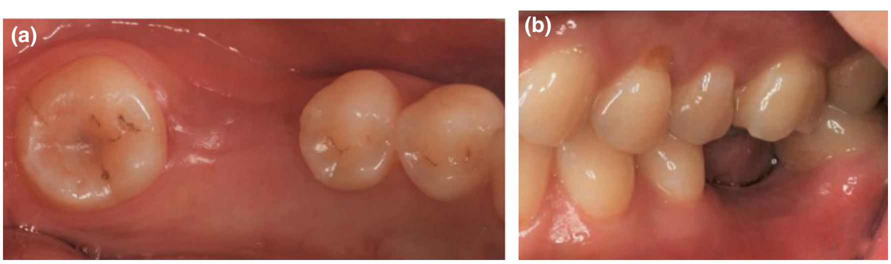

FIGURE 2 The edentulous area of a 29 year-old female(tooth 36 missed): (a) occlusal view, (b) buccal view

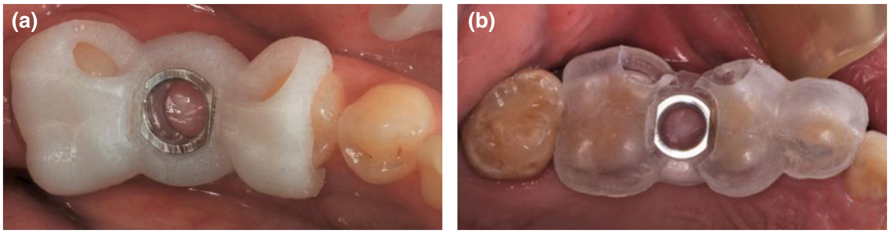

FIGURE 3 An FDM, 3D-printed surgical guide and a stereolithographic implant guide in place: (a) an FDM, 3D-printed surgical guide in place (the same patient in Figure 2, 36 missed). (b) a stereolithographic implant guide in place (another patient with 16 missing)

2.2.4 | Implant surgery and postoperative optical scan

All operations were conducted by the same clinician who was skilled at guided implant surgeries. The guides assisted preparation of the implant beds following the manufacturer's instructions, and bone-level implants (SLA®, Straumann, Switzerland) were inserted without guides (Figure 4). Scan bodies were then placed, and intraoral scans were carried out to obtain the 3D positions of the implants.

2.3 | Accuracy evaluation

The postoperative scan data were matched with the presurgical planning in the coDiagnostiX software, using point-to-point registration. The scan body was identified and used to deduce the actual implant position in the software; the planned and the placed positions of the implant were then compared by measuring the angular, 3D, mesiodistal, buccolingual, and apicocoronal deviations at the implant's shoulder and apex (Figure 5).

2.4 | Statistical analysis

Statistical analysis was performed using SPSS software (IBM SPSS Statistics v20.0; IBM Corp). The assumption of normality was justified using the Shapiro–Wilk test. The statistical data of angular deviation, 3D deviation at the implant's shoulder and implant apex, and buccolingual deviation at the implant's apex satisfied the normal distribution with homogeneity of variance, then independent samples *t*-tests were used to compare differences between the test and control groups. And these deviation values were expressed as the mean ± standard deviation (SD). The mean difference and 95% confidence interval of the difference were also calculated. The statistical data of mesiodistal deviation and apicocoronal deviation at the implant's shoulder and apex, as well as buccolingual deviation at the implant's shoulder did not satisfy the normal distribution, then non-parametric Mann–Whitney *U* tests were applied to evaluate the differences between the groups. These deviations were described using median, first quartile (Q_1) and third quartile (Q_3) values. To make the results more robust, two patients who each had two implants were then excluded. In the remaining data with one implant per patient, the analysis was repeated.

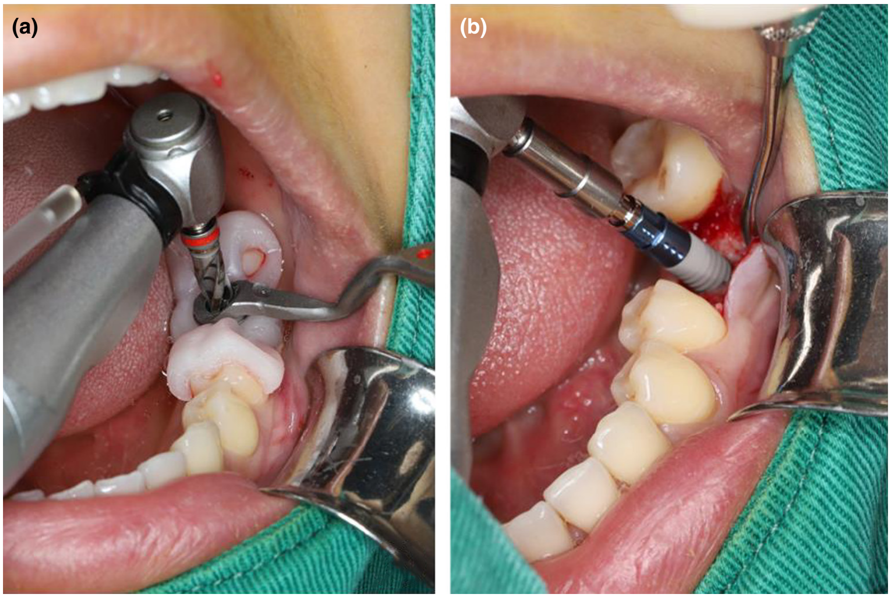

FIGURE 4 Implant surgery (the same patient as in Figure 2). (a) Implant bed preparation assisted by a surgical guide. (b) Implant insertion

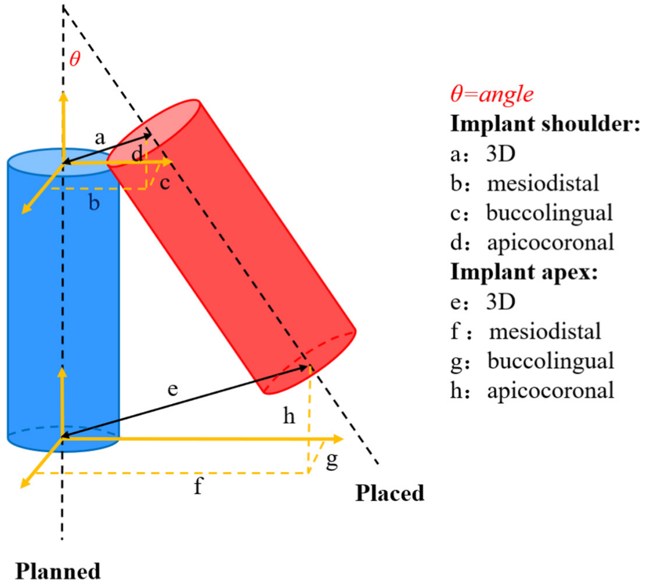

FIGURE 5 Schematic diagram of accuracy evaluation. The position of the placed (red) implant was compared with that of the planned (blue) implant

Statistical results for implant site distribution, diameter, and length are listed in the tables (Tables 1, 2). The deviation direction is counted up. Fisher's exact test was used to compare differences in implant site distribution and deviation direction between the two groups. All analyses considered $p < .05$ as significant.

3 | RESULTS

A total of 28 patients with a mean age of 35.6 years (range of 19–60 years) and a standard deviation of 11.21 years were enrolled in this study. There were 12 males (43%) and 16 females (57%). Overall, 30 bone-level implants were inserted. No surgical complications such as guide breakage or misfit of the drill guides occurred during surgeries. The 30 implants were distributed as follows: 14 in the maxilla and 16 in the mandible; nine in the premolar region, and 21 in the molar region (Table 1). The baseline of implant sites distribution between the two groups was comparable ($p > .05$). The test and control group each consisted of 15 implants. Table 2 lists the statistics of implant diameter and length. The direction of deviation was concerned and analyzed: the placed implants were more likely to be distal, buccal, and coronal in both groups. The differences in the deviation directions at the implant shoulder and apex between the two groups were not statistically significant ($p > .05$).

Statistical analysis of the deviation data used absolute values. The test and control group showed mean angular deviations of (4.23 ± 2.38) ° and (4.13 ± 2.42) °, respectively ($p > .05$). The mean difference was 0.09° between the groups, with a 95% confidence interval: [−1.70, 1.89], suggesting that the lower bound was smaller than the nominated margin of 2°. Their 3D deviations at the implant shoulder were (0.70 ± 0.44) mm and (0.55 ± 0.27) mm, ($p > .05$), and those at the implant apex were (1.25 ± 0.61) mm and (1.11 ± 0.54) mm, respectively ($p > .05$). The buccolingual deviations at the implant apex were (0.94 ± 0.53) mm and (0.85 ± 0.42) mm, respectively ($p > .05$) (Table 3, Figure 6).

The mesiodistal and apicocoronal deviations at the implant shoulder and apex, as well as buccolingual deviations at the implant shoulder also did not differ significantly between the groups ($p > .05$) (Table 4, Figure 7).

After excluding the data of two patients who each had two implants, the results of analysis confirmed that there were no significant differences of the deviations at the implant shoulder and apex between the two groups ($p > .05$).

4 | DISCUSSION

Postoperative evaluation identified no statistical differences in the outcome measures between the test and the control groups. The test group was non-inferior to the control group in terms of angular deviation. In this study, SLA technology using photopolymer and FDM technology using PLA were applied in the control and test

TABLE 1 Distribution of implant sites

Implant sites	Test (n = 15)	Control (n = 15)	p value	Total	Percentage
Maxilla	8	6	.715	14	46.7
Mandible	7	9		16	53.3
Premolar	5	4	1.000	9	30.0
Molar	10	11		21	70.0

TABLE 2 Summary of implant diameter and length

	4.1 mm × 10 mm	4.1 mm × 8 mm	4.8 mm × 10 mm	4.8 mm × 8 mm	4.1 mm × 12 mm	Total
Test	3	3	8	0	1	15
Control	5	0	7	3	0	15
Total	8	3	15	3	1	30

groups, respectively. Printing techniques and respective material can have an impact on printing accuracy (Rungrojwittayakul et al., 2020; Sommacal et al., 2018). For example, it was previously reported that the printing accuracy of a FDM printer using PLA filament was lower than that of a digital light processing (DLP) printer using a kind of photopolymer named e-shell 600 (Sommacal et al., 2018). Meanwhile, the printing accuracy of DLP technology was found to be lower than that of continuous liquid interface production (CLIP) technology with respective printing resin (Rungrojwittayakul et al., 2020). According to reports, the printing accuracy of SLA and FDM are approximately 25 ~ 100 μm and 100 ~ 150 μm, respectively (Ligon et al., 2017).

Although the printing accuracy of the guides may therefore have differed between the test group and control group, both groups achieved similar implant placement accuracy. The accuracy of implant placement in the clinical trial is the result of cumulative errors during the entire process, and printing accuracy is one of the influencing factors. It was reported that several factors, including the method of implant insertion, implanted jaw and flap surgery or not, were the main influencing factors which might reduce the impact of printing errors (D'Haese et al., 2017; Tahmaseb et al., 2014; Zhou et al., 2018). Even though the test group showed slightly greater deviation values than the control group, the difference was neither statistically nor clinically significant. Both groups' results were within the clinically acceptable range under the conditions of single posterior edentulous space.

Regarding the limited printing accuracy of the chairside, FDM, and 3D printer used here, only three units of guide can be printed precisely for a single-tooth vacancy. Although it is generally believed that in such cases two or three adjacent teeth can provide sufficient support to ensure retention of the guide (Kurbad, 2017), including additional teeth may further improve the stability of the guide. The different numbers of teeth supporting the guides (two for the test group and three for the control group) resulted in differing retention and stability that may have affected the accuracy evaluation results. While no statistical difference in the accuracy of implant placement between the two groups was found in this study, if the FDM, chairside, and 3D printer could print four-unit guides with high precision, the accuracy of the guidance might be higher.

Current literature shows implant placement using a surgical guide can significantly improve accuracy compared with freehand placement (Arisan et al., 2013; Smitkarn et al., 2019; Van Assche et al., 2012; Vermeulen, 2017). Moreover, compared with laboratory-fabricated guides, digitally designed and printed guides can achieve higher accuracy (Kernen et al., 2016; Kuhl et al., 2015; Tahmaseb et al., 2014). However, deviation appears inevitable (Derksen et al., 2019; Vercruyssen, Fortin, et al., 2014; Vercruyssen, Hultin, et al., 2014).

In a clinical trial comparing the accuracy of implant placement between fully guided implant surgery with a surgery guide and freehand implant surgery, the median (interquartile range) deviations in angles, shoulders, and apexes were 2.8 (2.6)°, 0.9 (0.8) mm and 1.2 (0.9) mm, respectively, in the implant guide group compared to 7.0

TABLE 3 Absolute accuracy values of outcome measures satisfying normal distribution

Outcome measures	FDM 3D-printed guide (test)				Stereolithographic guide (control)				*p* value	Mean difference	95% confidence interval of the difference	
	Mean	SD	Min	Max	Mean	SD	Min	Max			Lower	Upper
Angular deviation (°)	4.23	2.38	0.70	8.90	4.13	2.42	1.20	10.10	.916	0.09	−1.70	1.89
3D deviation at implant shoulder (mm)	0.70	0.44	0.22	1.70	0.55	0.27	0.17	1.02	.289	0.15	−0.13	0.42
3D deviation at implant apex (mm)	1.25	0.61	0.28	2.70	1.11	0.54	0.40	2.22	.538	0.13	−0.30	0.57
Buccolingual deviation at implant apex (mm)	0.94	0.53	0.14	2.09	0.85	0.42	0.25	1.92	.590	0.10	−0.26	0.45

Note: Independent sample *t*-test, $\alpha = 0.05$; Min: minimum; Max: maximum; SD: standard deviation.

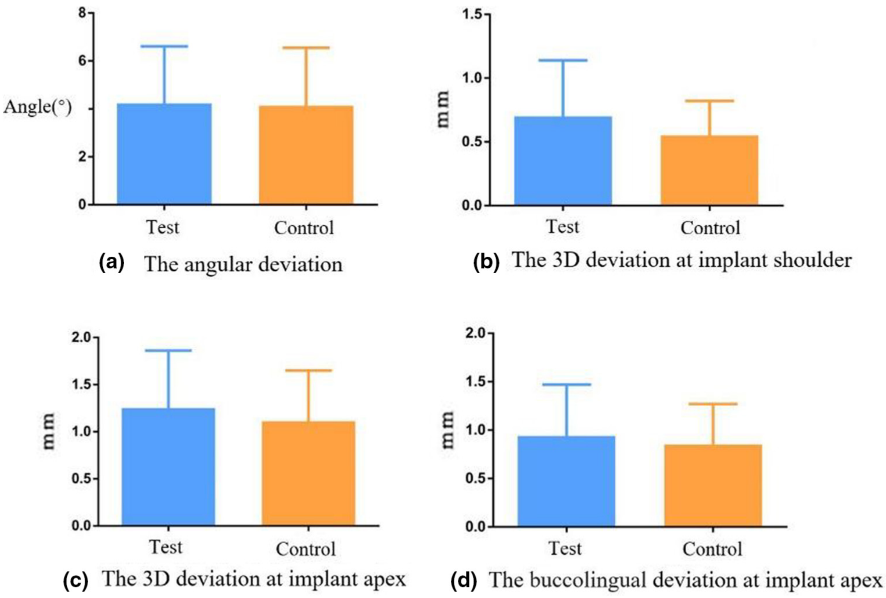

FIGURE 6 Histogram of the accuracy values of outcome measures satisfying normal distribution (error bars represent the standard deviation)

TABLE 4 Absolute accuracy values of outcome measures not satisfying normal distribution

Outcome measures		Group	Median	Q_1	Q_3	Max	Min	*p* value
Deviation at implant shoulder (mm)	Mesiodistal	Test	0.14	0.07	0.28	0.57	0.02	.506
		Control	0.12	0.02	0.26	0.79	0.00	
	Buccolingual	Test	0.26	0.18	0.35	1.00	0.04	.709
		Control	0.34	0.14	0.59	0.84	0.01	
	Apicocoronal	Test	0.31	0.25	0.77	1.42	0.04	.115
		Control	0.19	0.10	0.40	0.70	0.06	
Deviation at implant apex (mm)	Mesiodistal	Test	0.35	0.13	0.74	1.19	0.01	.852
		Control	0.41	0.12	0.58	1.83	0.04	
	Apicocoronal	Test	0.31	0.24	0.75	1.51	0.09	.078
		Control	0.16	0.12	0.38	0.66	0.08	

Note: Mann–Whitney *U* test, $\alpha = 0.05$; Min: minimum; Max: maximum.

(7.0)°, 1.3 (0.7) mm and 2.2 (1.2) mm, respectively, in the freehand group (Smitkarn et al., 2019). Meanwhile, in an in vitro study, it was reported that the mean angular deviation, and lateral deviation at the implant shoulder and apex were 7.63° and 2.19°, 1.27 mm and 0.42 mm, 1.28 mm and 0.52 mm, for the freehand method and guided surgery, respectively, with significant differences (Vermeulen, 2017).

A systematic review in 2014 (Tahmaseb et al., 2014) further demonstrated that average deviation at the implant shoulder was 0.84 mm, deviation at the implant apex was 1.15 mm, and average angular deviation was 3.28° when using tooth-supported guides to assist implant surgery in clinical studies. Using guides in partially guided surgery resulted in these average deviation values being 1.38 mm, 1.74 mm, and 4.35°, respectively. A more recent systematic review reported that using digital guides in clinical studies led to the average horizontal deviation being 1.10 mm at the implant shoulder and 1.40 mm at the implant apex, the average depth deviation being 0.74 mm, and the average angular deviation being 3.98° (Bover-Ramos et al., 2018). The present work reports accuracy comparable to the literature, indicating that chairside, FDM, 3D-printed surgical guides provide sufficient accuracy for clinical use under the conditions of single posterior edentulous space.

Complex clinical situations include many factors that may affect the accuracy of guided implant surgery: for example, mucosal thickness and limitations of the patient's mouth opening; the implant's length and site; the support type of the guide and whether it requires fixation screws; the surgeon's experience; and whether surgery is flapless and whether it is fully or partially guided (Abduo & Lau, 2020; Cassetta et al., 2015; Colombo et al., 2017; Derksen et al., 2019; D'Haese et al., 2017; Di Giacomo et al., 2012; Hammerle et al., 2015; Raico et al., 2017; Vermeulen, 2017; Zhou et al., 2018). A systematic review of 14 articles in 2018 (Zhou et al., 2018) concluded that implant placement in the mandible was more accurate than that in the maxilla, fully guided surgery was more precise than partially guided surgery, a flapless approach

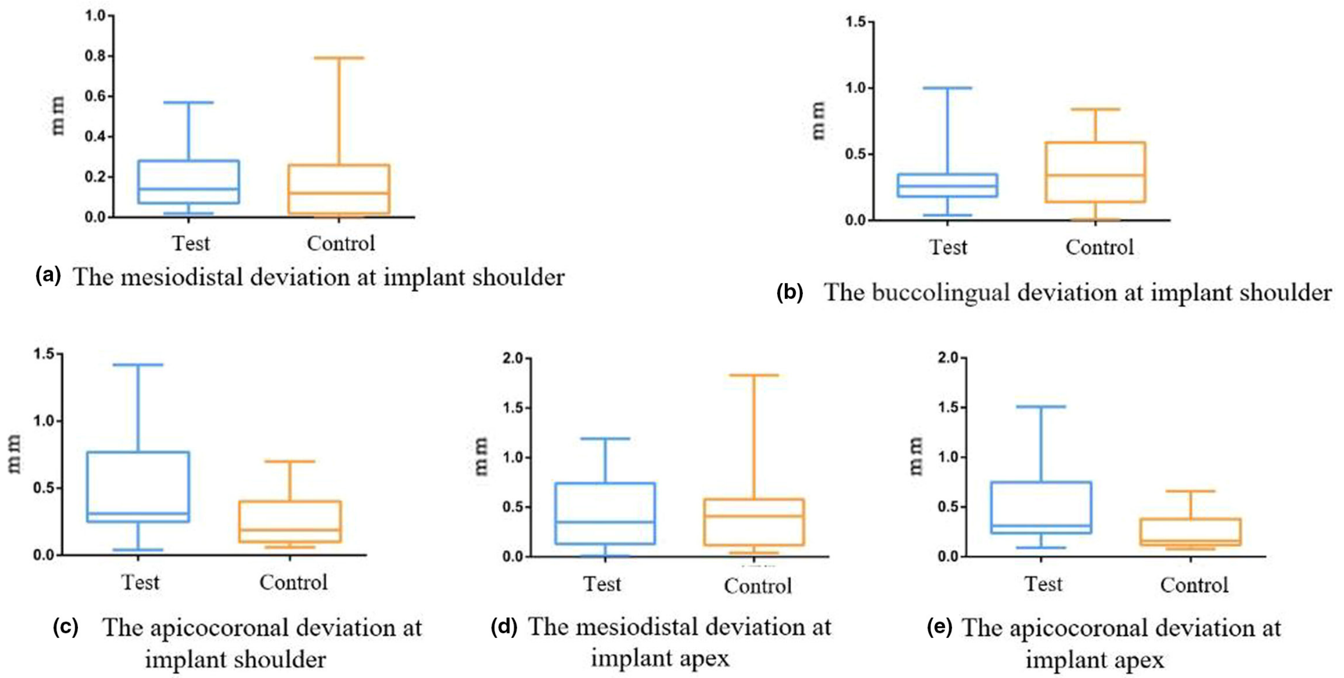

FIGURE 7 Box plots of the accuracy values of outcome measures not satisfying normal distribution (error bars represent the extremum)

was more accurate than a flap approach, and a guide with fixation screws had a smaller angular deviation than one without them. Many other studies also suggested that fully guided implant surgery showed a statistically superior accuracy to partially guided implant surgery (Bencharit et al., 2018; Tahmaseb et al., 2014; Zhou et al., 2018). Partial guidance, flap surgery, and a patient's restricted mouth opening were crucial influencing factors in the present study. The width of the keratinized mucosa is important to implant restoration, especially for mandibular posterior teeth (Schwarz et al., 2018; Tavelli et al., 2021). To preserve the keratinized mucosa as much as possible, flap surgeries were conducted in this study. Furthermore, the deviation between the placed implant and its design was related to differences between the design situation in the software and the actual situation in the patient's mouth, which might result from the quality of the CT images, and differences in viewing during design and surgery. Average CT image errors have been reported to be 0.06–0.54 mm (Eggers, et al., 2008, Loubele, et al., 2008).

Regarding the direction of deviation, there was no significant difference between the test and control group ($p > .05$). After preparation of the implant bed with the assistance of guides, the placed implants were more likely to be distal, buccal, and coronal in both groups. The reasons were supposed to be as follows: (1) The implant sites were all posterior teeth. Due to limitations of some patients' mouth openings, the drills needed to tilt towards mesial, which likely resulted in distal preparation of the implant beds. (2) As the lingual side of the bone is generally denser than the buccal side, it might have caused the preparation to lean toward the buccal side (Araujo et al., 2005; Chappuis et al., 2017). (3) The prepared depth was less than the designed implantation depth when the guide was not fully seated or slightly floating during hole preparation.

Despite its findings, the present study had some limitations. First, in order to avoid aesthetic risks, only posterior edentulous sites were considered. Second, fully guided surgery was not conducted. Although fully guided surgery is more accurate than partially guided surgery (Bencharit et al., 2018; D'Haese et al., 2017), it requires a wide edentulous space to fit a full-guided sleeve, and a large mouth opening in the posterior area (Bencharit et al., 2018). These deficiencies therefore limit its application. Third, the implant guides were used under conditions of single posterior edentulous space in the study. The chairside FDM 3D printer used in the study is yet hard to guarantee printing precision of the guide under conditions of multiple missing teeth due to its limitation: when printing guides with large span, complex supporting structures are needed, and the placement angle in the print setting software need to be altered. As a result, the accuracy of the guides may decrease during printing and removing support process.

Hence, FDM 3D-printed surgical guides used for anterior implant surgery, fully guided surgery and multiple missing teeth would be considered in the future and the accuracy needs to be further studied.

5 | CONCLUSIONS

Within the limitations of the study, implant placement with a chairside, FDM, 3D-printed implant guide achieved similar accuracy to a stereolithographic 3D-printed implant guide. The workflow for the design and fabrication of the chairside implant guide could improve clinical efficiency. Further research is needed especially for verification in anterior implant surgery and under more complex situations involving multiple missing teeth with a large cohort of subjects.

AUTHOR CONTRIBUTIONS

Yao Sun: Formal analysis (lead); investigation (lead); writing – original draft (lead). **Qian Ding:** Writing – review and editing (supporting). **Fusong Yuan:** Methodology (supporting). **Lei Zhang:** Conceptualization (lead); supervision (equal); writing – review and editing (lead). **Yuchun Sun:** Conceptualization (equal); supervision (equal); writing – review and editing (equal). **Qiufei Xie:** Supervision (equal).

ACKNOWLEDGMENTS

The authors express their sincere gratitude to associate professor Lin Zeng of Peking University Third Hospital for statistical analysis; associate professor Yijiao Zhao, engineer Xinyue Zhang, and students Kehui Deng, Rong Li, and Hefei Bai at the National Engineering Laboratory for Digital and Material Technology of Stomatology, for support during this study.

FUNDING INFORMATION

This study was supported by the Beijing Municipal Science and Technology Commission Research Fund (Z161100000116092), the Beijing Natural Science Foundation (7192233), and the Capital's Funds for Health Improvement and Research (2020–2-4104).

CONFLICT OF INTEREST

The authors report no conflicts of interest related to this study.

DATA AVAILABILITY STATEMENT

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

ORCID

Yao Sun https://orcid.org/0000-0002-1193-6088

REFERENCES

Abduo, J., & Lau, D. (2020). Accuracy of static computer-assisted implant placement in anterior and posterior sites by clinicians new to implant dentistry: In vitro comparison of fully guided, pilot-guided, and freehand protocols. *International Journal of Implant Dentistry*, *6*, 10.

Alharbi, N., Wismeijer, D., & Osman, R. B. (2017). Additive manufacturing techniques in prosthodontics: Where do we currently stand? A critical review. *The International Journal of Prosthodontics*, *30*, 474–484.

Araujo, M. G., Sukekava, F., Wennstrom, J. L., & Lindhe, J. (2005). Ridge alterations following implant placement in fresh extraction sockets: An experimental study in the dog. *Journal of Clinical Periodontology*, *32*, 645–652.

Arisan, V., Karabuda, C. Z., Mumcu, E., & Ozdemir, T. (2013). Implant positioning errors in freehand and computer-aided placement methods: A single-blind clinical comparative study. *The International Journal of Oral & Maxillofacial Implants*, *28*, 190–204.

Bencharit, S., Staffen, A., Yeung, M., Whitley, D. R., Laskin, D. M., & Deeb, G. R. (2018). In vivo tooth-supported implant surgical guides fabricated with desktop stereolithographic printers: Fully guided surgery is more accurate than partially guided surgery. *Journal of Oral and Maxillofacial Surgery*, *76*, 1431–1439.

Boursier, J. F., Fournet, A., Bassanino, J., Manassero, M., Bedu, A. S., & Leperlier, D. (2018). Reproducibility, accuracy and effect of autoclave sterilization on a thermoplastic three-dimensional model printed by a desktop fused deposition modelling three-dimensional printer. *Veterinary and Comparative Orthopaedics and Traumatology*, *31*, 422–430.

Bover-Ramos, F., Vina-Almunia, J., Cervera-Ballester, J., Penarrocha-Diago, M., & Garcia-Mira, B. (2018). Accuracy of implant placement with computer-guided surgery: A systematic review and meta-analysis comparing cadaver, clinical, and in vitro studies. *The International Journal of Oral & Maxillofacial Implants*, *33*, 101–115.

Calcagnile, P., Cacciatore, G., Demitri, C., Montagna, F., & Esposito, C. C. (2018). A feasibility study of processing polydimethylsiloxane(−) sodium carboxymethylcellulose composites by a low-cost fused deposition modeling 3D printer. *Materials (Basel)*, *11*(9), 1578.

Cassetta, M., Di Mambro, A., Di Giorgio, G., Stefanelli, L. V., & Barbato, E. (2015). The influence of the tolerance between mechanical components on the accuracy of implants inserted with a stereolithographic surgical guide: A retrospective clinical study. *Clinical Implant Dentistry and Related Research*, *17*, 580–588.

Chappuis, V., Araujo, M. G., & Buser, D. (2017). Clinical relevance of dimensional bone and soft tissue alterations post-extraction in esthetic sites. *Periodontology 2000*, *73*, 73–83.

Chen, H., Yang, X., Chen, L., Wang, Y., & Sun, Y. (2016). Application of FDM three-dimensional printing technology in the digital manufacture of custom edentulous mandible trays. *Scientific Reports*, *6*, 19207.

Colombo, M., Mangano, C., Mijiritsky, E., Krebs, M., Hauschild, U., & Fortin, T. (2017). Clinical applications and effectiveness of guided implant surgery: A critical review based on randomized controlled trials. *BMC Oral Health*, *17*, 150.

Dawood, A., Marti, M. B., Sauret-Jackson, V., & Darwood, A. (2015). 3D printing in dentistry. *British Dental Journal*, *219*, 521–529.

Deeb, G. R., Allen, R. K., Hall, V. P., Whitley, D. R., Laskin, D. M., & Bencharit, S. (2017). How accurate are implant surgical guides produced with desktop stereolithographic 3-Dimentional printers? *Journal of Oral and Maxillofacial Surgery*, *75*, 2551–2559.

Derksen, W., Wismeijer, D., Flugge, T., Hassan, B., & Tahmaseb, A. (2019). The accuracy of computer-guided implant surgery with tooth-supported, digitally designed drill guides based on CBCT and intraoral scanning. A prospective cohort study. *Clinical Oral Implants Research*, *30*, 1005–1015.

D'Haese, J., Ackhurst, J., Wismeijer, D., De Bruyn, H., & Tahmaseb, A. (2017). Current state of the art of computer-guided implant surgery. *Periodontology 2000*, *73*, 121–133.

Di Giacomo, G. A., Da, S. J., Da, S. A., Paschoal, G. H., Cury, P. R., & Szarf, G. (2012). Accuracy and complications of computer-designed selective laser sintering surgical guides for flapless dental implant placement and immediate definitive prosthesis installation. *Journal of Periodontology*, *83*, 410–419.

Eggers, G., Klein, J., Welzel, T., & Muhling, J. (2008). Geometric accuracy of digital volume tomography and conventional computed tomography. *Br J Oral Maxillofac Surg*, *46*, 639–644.

Garber, D. A., & Belser, U. C. (1995). Restoration-driven implant placement with restoration-generated site development. *Compendium of Continuing Education in Dentistry*, *16*, 796 798-802, 804.

Hammerle, C. H., Cordaro, L., van Assche, N., Benic, G. I., Bornstein, M., Gamper, F., Gotfredsen, K., Harris, D., Hurzeler, M., Jacobs, R., Kapos, T., Kohal, R. J., Patzelt, S. B., Sailer, I., Tahmaseb, A., Vercruyssen, M., & Wismeijer, D. (2015). Digital technologies to support planning, treatment, and fabrication processes and outcome assessments in implant dentistry. Summary and consensus statements. The 4th EAO consensus conference 2015. *Clinical Oral Implants Research*, *26*(Suppl 11), 97–101.

Hultin, M., Svensson, K. G., & Trulsson, M. (2012). Clinical advantages of computer-guided implant placement: A systematic review. *Clinical Oral Implants Research*, *23*(Suppl 6), 124–135.

Jung, R. E., Schneider, D., Ganeles, J., Wismeijer, D., Zwahlen, M., Hammerle, C. H., & Tahmaseb, A. (2009). Computer technology applications in surgical implant dentistry: A systematic review. *The International Journal of Oral & Maxillofacial Implants*, *24*(Suppl), 92–109.

Kernen, F., Benic, G. I., Payer, M., Schar, A., Muller-Gerbl, M., Filippi, A., & Kuhl, S. (2016). Accuracy of three-dimensional printed templates for guided implant placement based on matching a surface scan with CBCT. *Clinical Implant Dentistry and Related Research*, *18*, 762–768.

Kuhl, S., Payer, M., Zitzmann, N. U., Lambrecht, J. T., & Filippi, A. (2015). Technical accuracy of printed surgical templates for guided implant surgery with the coDiagnostiX software. *Clinical Implant Dentistry and Related Research*, *17*(Suppl 1), e177–e182.

Kurbad, A. (2017). Tooth-supported surgical guides for guided placement of single-tooth implants. *International Journal of Computerized Dentistry*, *20*, 93–105.

Ligon, S. C., Liska, R., Stampfl, J., Gurr, M., & Mulhaupt, R. (2017). Polymers for 3D printing and customized additive manufacturing. *Chemical Reviews*, *117*, 10212–10290.

Loubele, M., Maes, F., Jacobs, R., van Steenberghe, D., White, S. C., & Suetens, P. (2008). Comparative study of image quality for MSCT and CBCT scanners for dentomaxillofacial radiology applications. *Radiat Prot Dosimetry*, *129*, 222–226.

Madhavan, N. K., Nair, N. R., & John, R. P. (2010). An overview of the recent developments in polylactide (PLA) research. *Bioresource Technology*, *101*, 8493–8501.

Molinero-Mourelle, P., Canals, S., Gomez-Polo, M., Sola-Ruiz, M. F., Del, R. H. J., & Vinuela, A. C. (2018). Polylactic acid as a material for three-dimensional printing of provisional restorations. *The International Journal of Prosthodontics*, *31*, 349–350.

Pieralli, S., Spies, B. C., Hromadnik, V., Nicic, R., Beuer, F., & Wesemann, C. (2020). How accurate is oral implant installation using surgical guides printed from a degradable and steam-sterilized biopolymer? *Journal of Clinical Medicine*, *9*, 2322.

Raico, G. Y., Da, S. I., Mukai, E., Morimoto, S., Sesma, N., & Cordaro, L. (2017). Accuracy comparison of guided surgery for dental implants according to the tissue of support: A systematic review and meta-analysis. *Clinical Oral Implants Research*, *28*, 602–612.

Rungrojwittayakul, O., Kan, J. Y., Shiozaki, K., Swamidass, R. S., Goodacre, B. J., Goodacre, C. J., & Lozada, J. L. (2020). Accuracy of 3D printed models created by two technologies of printers with different designs of model base. *Journal of Prosthodontics*, *29*, 124–128.

Schwarz, F., Becker, J., Civale, S., Sahin, D., Iglhaut, T., & Iglhaut, G. (2018). Influence of the width of keratinized tissue on the development and resolution of experimental peri-implant mucositis lesions in humans. *Clinical Oral Implants Research*, *29*, 576–582.

Smitkarn, P., Subbalekha, K., Mattheos, N., & Pimkhaokham, A. (2019). The accuracy of single-tooth implants placed using fully digital-guided surgery and freehand implant surgery. *Journal of Clinical Periodontology*, *46*, 949–957.

Sommacal, B., Savic, M., Filippi, A., Kuhl, S., & Thieringer, F. M. (2018). Evaluation of two 3D printers for guided implant surgery. *The International Journal of Oral & Maxillofacial Implants*, *33*, 743–746.

Sun, Y., Ding, Q., Tang, L., Zhang, L., Sun, Y., & Xie, Q. (2019). Accuracy of a chairside fused deposition modeling 3D-printed single-tooth surgical template for implant placement: An in vitro comparison with a light cured template. *Journal of Cranio-Maxillo-Facial Surgery*, *47*, 1216–1221.

Tahmaseb, A., Wismeijer, D., Coucke, W., & Derksen, W. (2014). Computer technology applications in surgical implant dentistry: A systematic review. *The International Journal of Oral & Maxillofacial Implants*, *29*(Suppl), 25–42.

Tavelli, L., Barootchi, S., Avila-Ortiz, G., Urban, I. A., Giannobile, W. V., & Wang, H. L. (2021). Peri-implant soft tissue phenotype modification and its impact on peri-implant health: A systematic review and network meta-analysis. *Journal of Periodontology*, *92*(1), 21–44.

Torabi, K., Farjood, E., & Hamedani, S. (2015). Rapid prototyping technologies and their applications in prosthodontics, a review of literature. *Journal of Dentistry (Shiraz)*, *16*, 1–9.

Van Assche, N., Vercruyssen, M., Coucke, W., Teughels, W., Jacobs, R., & Quirynen, M. (2012). Accuracy of computer-aided implant placement. *Clinical Oral Implants Research*, *23*(Suppl 6), 112–123.

Vercruyssen, M., Fortin, T., Widmann, G., Jacobs, R., & Quirynen, M. (2014). Different techniques of static/dynamic guided implant surgery: Modalities and indications. *Periodontology 2000*, *66*, 214–227.

Vercruyssen, M., Hultin, M., Van Assche, N., Svensson, K., Naert, I., & Quirynen, M. (2014). Guided surgery: Accuracy and efficacy. *Periodontology 2000*, *66*, 228–246.

Vermeulen, J. (2017). The accuracy of implant placement by experienced surgeons: Guided vs freehand approach in a simulated plastic model. *The International Journal of Oral & Maxillofacial Implants*, *32*, 617–624.

Whitley, D. R., Eidson, R. S., Rudek, I., & Bencharit, S. (2017). In-office fabrication of dental implant surgical guides using desktop stereolithographic printing and implant treatment planning software: A clinical report. *The Journal of Prosthetic Dentistry*, *118*, 256–263.

Yuan, F., Sun, Y., Zhang, L., & Sun, Y. (2019). Accuracy of chair-side fused-deposition modelling for dental applications. *Rapid Prototyping Journal*, *25*, 587–863.

Zhou, W., Liu, Z., Song, L., Kuo, C. L., & Shafer, D. M. (2018). Clinical factors affecting the accuracy of guided implant surgery-a systematic review and meta-analysis. *The Journal of Evidence-Based Dental Practice*, *18*, 28–40.

How to cite this article: Sun, Y., Ding, Q., Yuan, F., Zhang, L., Sun, Y., & Xie, Q. (2022). Accuracy of a chairside, fused deposition modeling three-dimensional-printed, single tooth surgical guide for implant placement: A randomized controlled clinical trial. *Clinical Oral Implants Research*, *33*, 1000–1009. https://doi.org/10.1111/clr.13981