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The Effect of Different Socket Morphologies of a Maxillary Central Incisor on the Accuracy of Immediate Implants Placed With Freehand or Guided Surgery—An In Vitro Study

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ABSTRACT

Objective: To evaluate the effect of socket morphology of a maxillary central incisor on accuracy of single implants placed with freehand or static guided surgery in simulated extraction sockets.

Materials and Methods: An anatomic central incisor was digitally designed and subtracted from the model to create socket morphology 1 (SM1), socket morphology 2 (SM2), and socket morphology 3 (SM3) simulating a central, retroclined, and proclined tooth. 90 implants were placed with freehand (FH); pilot guided (PG) and fully guided (FG) protocols in 30 models of SM1, SM2 and SM3 each. Implant accuracy was measured for vertical deviation (MVP), maximum horizontal deviation at implant platform (MHP) and apex (MHA), buccolingual (BLP, BLA), mesiodistal (MDP, MDA), and global angular deviation (GAD) deviations.

Results: The effect of interaction between SM and protocol was significant only on MVP ($p = 0.03$) and GAD ($p = 0.000$). Individual effect of SM was significant for all variables except mesiodistal deviation. Significant difference was observed among all groups for MHA and BLP, between SM1 and SM2 for all variables except mesiodistal deviation, between SM2 and SM3 for MHP and SM1 and SM3 for BLA ($p < 0.05$). Implant accuracy was almost similar with FG or PG protocol ($p > 0.05$) except for MVP (FG vs. PG $= 0.01$). Buccolingual inaccuracies of implants were higher than mesiodistal deviations.

Conclusions: Vertical, horizontal, and angular deviations were highest in SM2 and least in group SM1. Within each socket, higher implant accuracy was observed with guided protocols than freehand placement. Results of this in vitro study should be interpreted with caution as the outcome may be different in real clinical settings.

1 | Introduction

The anterior immediate implant placement (IIP) is a technique sensitive procedure, and it requires a meticulous planning for a successful surgical and aesthetic outcome. Decisions regarding implant position and dimensions are based on the clinical assessment and radiographic findings on cone beam computed tomography (CBCT) when implants are placed freehand (Chen et al. 2022). Computer-assisted implant planning and static-guided implant placement can be undertaken either with a pilot-guided (PG) or fully guided (FG) protocol, and aim is to plan the implant position conducive for an aesthetic and functional restoration, also referred as prosthesis-driven planning (Levine et al. 2017). Many factors have been recommended for consideration before planning for an anterior immediate implant like soft tissue phenotype, buccal wall thickness, anatomy of the

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alveolar crest, and availability of apical bone for primary stability (Alevizakos et al. 2019; Lee et al. 2020).

Clinically, the first step for IIP requires the atraumatic extraction of the root just before implant placement. Different classification systems have been put forth according to different root positions of a maxillary central incisor in the socket (Kan et al. 2011, 2018; Soumya et al. 2021). Rodrigues et al. (2023) emphasized the relevance of sagittal root position of anterior teeth for long-term stability of hard and soft tissues around immediate implants. A significant relation has also been reported between root position, its angulation in the alveolar socket and the direction of emergence of the clinical crown. According to the observations of radiographic study by Gluckman, the most prevalent radial root position was Class II with retroclined tooth position and Class I was least prevalent where the tooth was centrally located within the socket (Gluckman et al. 2018). Following the direction of root during osteotomy may lead to perforation of the labial cortical plate in Class II or need for cement-retained prosthesis in Class I root position. So, the authors suggested to consider palatal osteotomy with or without grafting to enable fabrication of a screw-retained prosthesis. Although the findings of these observational studies cannot be directly extrapolated to the clinical scenario, it seems pertinent to plan an anterior immediate implant on a case-to-case basis with due consideration to root position, root angulation, and post extraction socket morphology.

Chen et al. (2018) attributed socket morphology as an important reason for facial deviation of immediate implants, as the drill and the implant have a tendency to follow the path of least resistance, which is same as the position of root in the socket. Facial deviation of the implant is common with freehand protocol, while many studies have reported this shift even after guided implant placement (Koticha et al. 2012; van Assche and Quirynen 2010). Kan et al. (2018) suggested that buccal position (Class I) of root is more favorable as implant gets its stability from the palatal bone while Class II, III, and IV require more stringent planning in terms of adjuvant bone grafting procedures. One of the significant implications of close approximation of root with buccal wall can be its perforation during osteotomy. On the other hand, if the root position is palatal, anchorage has to be taken from the buccal bone, which can undergo faster resorption being trabecular in nature.

Numerous studies have evaluated the accuracy of implants placed in healed anterior or posterior sockets with different surgical protocols (Abduo and Lau 2020; Chandran et al. 2023; Tan et al. 2018). Most of the in vitro or in vivo studies have reported highest implant accuracy with FG protocol followed by PG and FH protocols (Chandran et al. 2023; Chen et al. 2022; Guentsch et al. 2022, 2021; Nickenig et al. 2010; Yeung et al. 2020). The primary focus of these studies was to compare the implant accuracy with freehand vs. computer-assisted surgery, with variation in site (anterior vs. posterior), implant systems, surgical guide designs, healed vs. fresh extraction sites or the experience of the operator. But none of these studies have specifically taken socket morphology into account. Therefore, the primary objective of this study was to evaluate the effect of different socket morphologies of a maxillary central incisor on accuracy of immediate implants inserted with freehand or guided surgical protocols The null hypothesis was that accuracy of an anterior immediate implant will be same in different socket morphologies with no influence of class of root position and surgical protocol.

2 | Materials and Methods

This in vitro study was conducted at the Melbourne Dental School and followed the checklist for Reporting In vitro Study (CRIS guidelines) during planning and execution of the study (Krithikadatta et al. 2014).

2.1 | Digital Designing of Post Extraction Sockets With Different Morphologies

A fully dentate maxillary model (Nissin Dental Products Inc., Kyoto, Japan) was scanned using a desktop scanner (Identica T500; Medit Identica, DT Technologies, Davenport, IA) to derive a digital model in surface tessellation language (STL) format. A Cone beam Computed tomography (CBCT) was undertaken of the same model to get the cross sectional DICOM file (iCAT; Imaging Sciences International INC., USA, 20 kVP, 5 mA). An anatomic right maxillary central incisor was digitally designed and subtracted from the digital model leaving behind three different socket morphologies designated as SM1, SM2 and SM3 (Autodesk Meshmixer, USA) (Figure 1a–c). These sockets were based on Class I, II, and III radial root positions and simulated

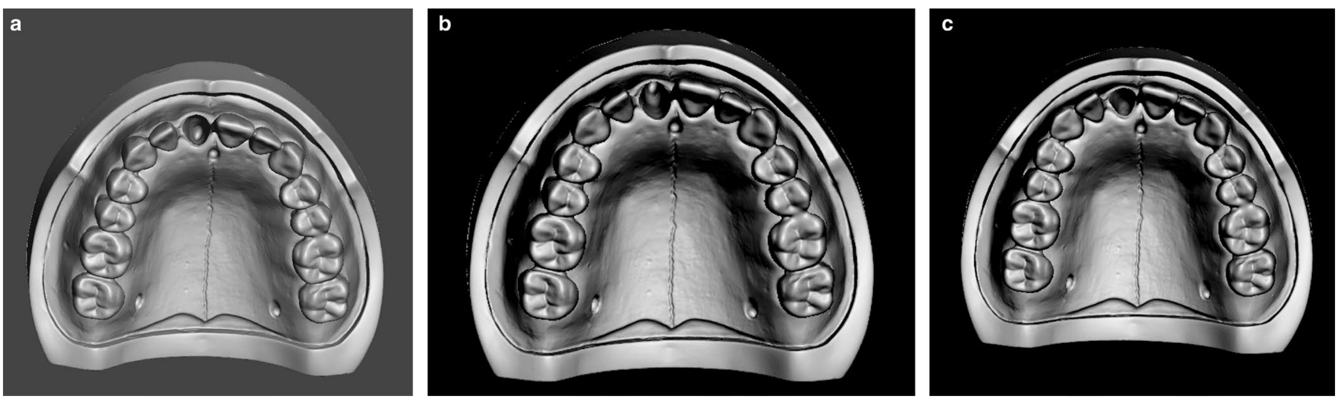

FIGURE 1 | Digitally designed socket morphologies of maxillary central incisor (a) Socket morphology (SM1) (b) Socket morphology (SM2) (c) Socket morphology (SM3).

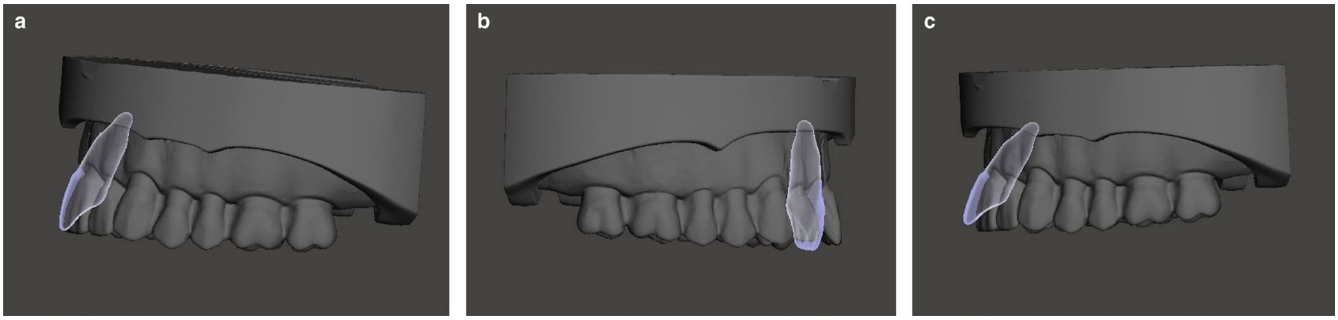

FIGURE 2 | Different socket morphologies according to root position in socket (a) socket morphology (SM1) (b) socket morphology (SM2) (c) socket morphology (SM3).

three postextraction sockets in clinical scenario as centrally placed root in the socket (SM1), resembling a retroclined tooth (SM2) and a proclined tooth (SM3) (Figure 2a–c) (Gluckman et al. 2018).

2.2 | Surgical Planning for Implant Placement and Guide Fabrication

Surgical planning was carried by an experienced periodontist (L.N.) on superimposed DICOM and STL files of master model according to standard recommendation for implant placement in fresh extraction socket of a maxillary central incisor. Final implant position was in accordance with a prosthesis-driven approach to allow screw-retained immediate provisional crown (coDiagnostiX, Dental Wings, Montreal, Canada) (Figure 3). A bone level tapered implant (Straumann, 4.1*12 mm) was selected from the software library suitable for all socket morphologies. Surgical guides were designed and stainless-steel T-Sleeves with 2.2 mm and 5 mm diameter (Straumann AG, Basel, Switzerland) were selected for pilot-guided (PG) and fully guided (FG) protocols respectively (Figure 3). Guide sleeves were fitted precisely in the printed guides by a trained technician. Printing of all models was done in resin on the same printer (NextDent 5100; 3D systems, USA) after appropriate calibration to ensure accuracy. Complete seating of the surgical guides on all models was ensured through inspection windows and stability was checked before implant placement. No modification was done in any of the surgical model or guide before or during the implant placement.

2.3 | Sample Size and Group Allocation

Sample size was calculated using G*Power software (version 3.1.9.2; University of Dusseldorf, Dusseldorf, Germany) and mean deviation of implant platform reported in a previous study after anterior implant placement with FG (0.5 ± 0.25 mm) or PG (1.2 ± 0.5 mm) protocol (Abduo and Lau 2020). By applying 80% statistical power, alpha = 0.05, and effect size of 1.77, minimum sample size of 10 was required for each intervention. Accordingly, a total number of 90 printed surgical models were allocated to three main groups based on socket morphology as Group SM1, Group SM2 and Group SM3 ($n = 30$). In each group, implants were placed by freehand (FH/$n = 10$), pilot-guided (PG/$n = 10$) and fully guided (FG/$n = 10$) protocols.

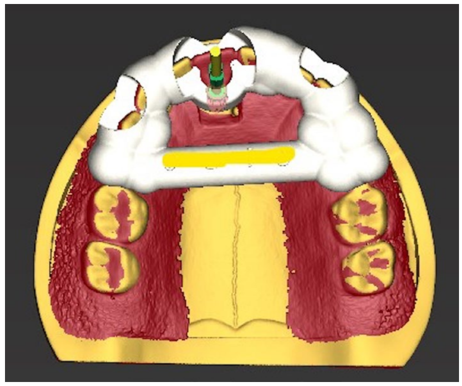

FIGURE 3 | Prosthesis-driven implant planning with pilot-guided sleeve.

2.4 | Surgical Protocol

Models were stabilized in a phantom head (to simulate a clinical set up) and dental chair position was fixed according to the arch position and comfort of the operator. In each group, models were numbered sequentially from 1 to 30 with symbolic color coding to categorize them according to different surgical protocols. On 10 models of each group, first freehand implant placement was done according to the radiographic planning on DICOM files, followed by PG and FG protocols on another set of models. This sequence has been recommended in previous studies to maintain uniformity and to avoid any prior practice with the surgical guides (Vermeulen 2017, Abduo and Lau 2021). Osteotomy preparation followed recommended drill sequence and drilling speeds from the manufacturer (Straumann AG) and was based on manual navigation for the FH protocol. Osteotomy with a 2.2 mm pilot drill was done with the surgical guide in position while subsequent drilling and implant placement were done freehand in PG protocol while full osteotomy was done using drills and their corresponding drill handles/spoons with stops in FG protocol (Abduo and Lau 2021) (Figure 4a–d).

2.5 | Evaluation of Implant Position Accuracy

An implant specific scan body (CARES RC Mono scan body, 4.1 × 10 mm, PEEK, Straumann) was hand tightened on each implant with a driver. Surgical models were scanned with same

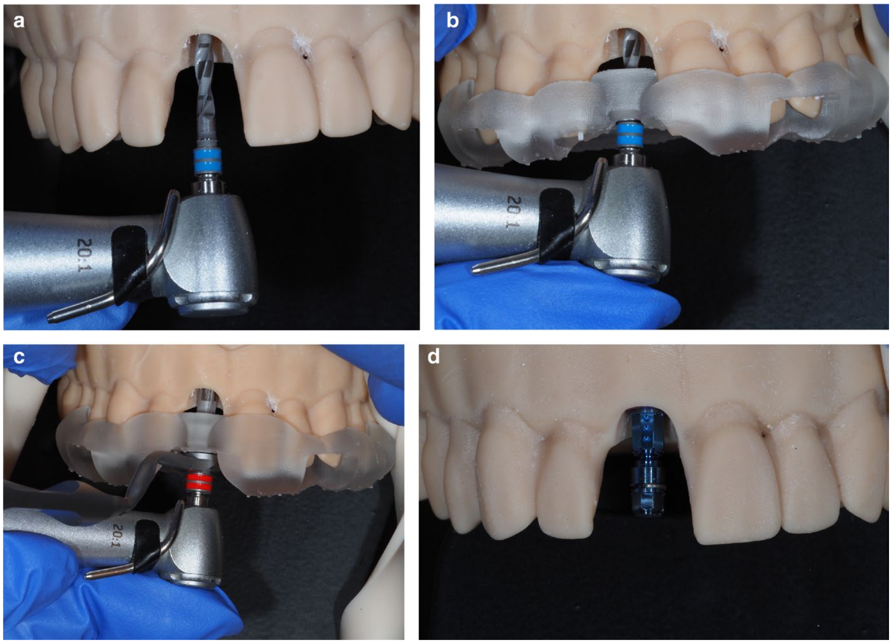

FIGURE 4 | Implant placement (a) freehand drilling; (b) pilot-guided placement (c) fully guided placement (d) final implant position.

desktop scanner following the number sequence to generate virtual surgical models in STL format. For measuring the deviations, coordinates of planned and placed implants were exported from designing software (exocad GmbH, Germany) and saved as new STL files by a trained technician (Figure 5). Each STL file of placed implant with fixed coordinates was then imported into a measuring software (Geomagic control X, Oqton,) and superimposed with the STL file of the originally planned implant and master model to measure vertical deviation (MVP), maximum horizontal deviation (MHP) at implant platform, maximum horizontal deviation of implant apex (MHA), and global angular deviation (GAD). Vertical deviation was measured by taking two corresponding points at the respective platforms of implants (Figure 6a) while maximum horizontal deviations were measured as linear distance (in millimeters) between centers of planned and placed implants at platform and at apex (Figure 6b). GAD was evaluated by measuring the angles (in degrees) between the vectors of long axes of planned and each placed implant (Figure 6c). Buccolingual and mesiodistal deviations at platform and apex (BLP, BLA, MDP, MDA) were measured by marking points from the centers of the planned and placed implants. All the measurements were done by a single researcher who received training for operating the software and was blinded with regards to the implant placement protocol. Multiple random samples were cross checked by a secondary assessor to ensure accuracy of data. Measurements were tabulated in Microsoft excel sheet and analyzed in statistics software (IBM Statistical Package for Social Sciences version 25.0).

2.6 | Statistical Analysis

Data were checked for normality with Shapiro Wilk test and equality of variance was checked by Levene's test. Descriptive analysis was done to calculate mean ± standard deviation (SD) for each variable. Effect of socket morphology and surgical protocol was calculated with two-way analysis of variance to know the interaction of both factors on outcome variables. Tukey's HSD test was used for post hoc analysis. $p < 0.05$ was considered statistically significant and confidence interval was set at 95%.

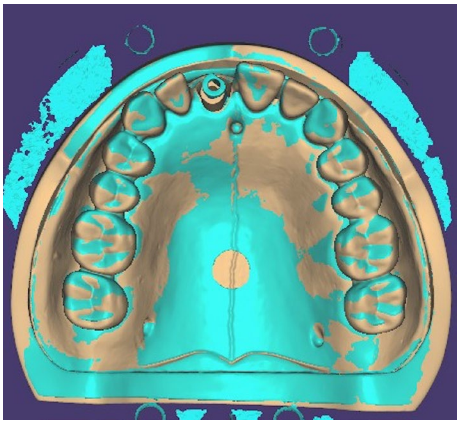

FIGURE 5 | Superimposition of planned and placed implant.

3 | Results

Mean vertical and horizontal deviations of implants in all groups have been represented in Figure 9.

3.1 | Mean Vertical Deviation of Implant Platform (MVP)

MVP was with <1 mm with FG, between 0.9–1.2 mm with PG and 1.3–1.6 mm with FH protocols in all groups. Implant placement with PG or FH group led to highest variation in SM2. Within each group, overall difference due to protocol was

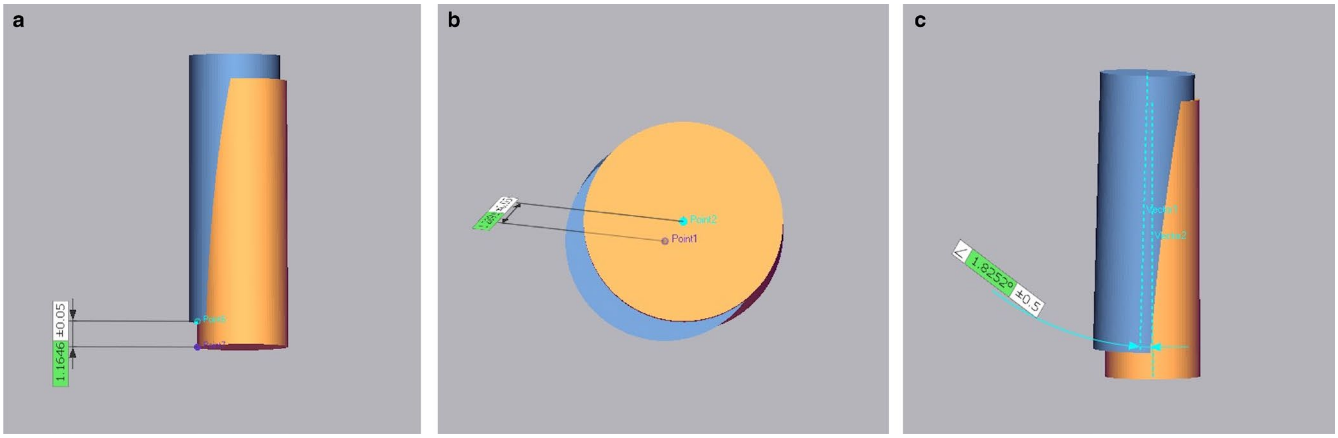

FIGURE 6 | Measurement of deviation (a) vertical deviation of implant platform (b) maximum horizontal deviation (c) global angular deviation.

significant in all groups. Intergroup difference was significant only between SM1 and SM2 ($p = 0.03$). Combined effect of socket morphology and protocol was significant ($p = 0.04$) on MVP, with significant influence of both factors (Table 1).

3.2 | Maximum Horizontal Deviation of Implant Platform and Apex (MHP, MHA)

Mean MHP and MHA were almost similar with FG and PG protocols (1.2–1.5 mm, $p > 0.05$) and higher with FH protocol (1.5–1.8 mm). With all surgical protocols, MHP and MHA were highest in SM2 while lowest deviation was noticed in SM1. MHP was higher than apical deviations in SM1 while it was otherwise in SM2 and SM3, irrespective of surgical protocol. Intergroup difference showed significant deviation of implant platform (MHP) between SM1 and SM2 ($p = 0.000$) and SM2 and SM3 ($p = 0.006$) and among all groups at apex (MHA; $p = 0.000$). Individual effect of SM and protocol was more relevant on MHP and MHA than their combined interaction (Tables 2 and 3).

3.3 | Buccolingual and Mesiodistal Deviations of Implant Platform and Apex (BLP, BLA, MDP, and MDA)

Mean BLP was less than 1 mm in group SM1, up to 1.5 mm in SM2 and ≤1.3 mm in SM3. A statistically significant difference was observed among groups (SM1 and SM2 and SM1 and SM3, $p = 0.000$; SM2 and SM3, $p = 0.001$). In all groups, mean BLA were higher than that of platform. Highest inaccuracy was observed in SM2, and intergroup difference was significant between SM1 and SM2 and SM1 and SM3 ($p = 0.000$). The effect of surgical protocol on BLP was significant only in SM3 ($p = 0.02$), but in all groups for BLA. Combined interaction of SM and protocol was nonsignificant, while main effects of individual factors showed significant difference for both BLP and BLA (Tables 4 and 5). Mesio-distal deviations of implant platform were less than 1 mm with guided protocols. Effect of protocol was significant in group SM1 ($p = 0.001$) and SM2 ($p = 0.03$). Deviations at apex were lesser than those at platform with no effect of SM or protocol (Tables 6 and 7).

In SM1, most of the implant platforms were deviated toward mesiobuccal direction. All implant apices showed mesial deviation with higher predilection toward the lingual direction. Interprotocol variation was high, and implants placed with FH protocol showed more skewed distribution and higher deviations as compared to FG or PG protocols (Figures 7a and 8a). In SM2, deviations of all platforms were skewed toward mesiobuccal direction except for few implants placed with FG protocol, which were deviated toward distobuccal direction. At apex, implants placed with FG and FH protocols showed very high variation, with a greater number of implants deviated toward mesiobuccal direction. With PG protocol, all implant apices were deviated in mesiobuccal direction (Figures 7b and 8b). In SM3, deviations of implant platforms were more noticeable in mesiobuccal direction with all surgical protocols while at apex, most of the implants were deviated towards mesiolingual direction (Figures 7c and 8c).

3.4 | Global Angular Deviation (GAD)

In Group SM1, mean GAD was 1.9°, 2.2°, and 2.38° with FG, PG, and FH protocols respectively ($p = 0.2$). Maximum deviation of approximately 2.9° was observed with guided protocols and 3.2° with FH protocol. Mean GAD in SM2 with FG, PG, and FH was 3.1°, 2.8°, and 4.2°, respectively with significant difference between guided and FH protocols (FG vs. FH, $p = 0.001$; PG vs. FH, $p = 0.000$). Maximum GAD was approximately 4° with guided protocols and 5.2° with FH. In group SM3, mean GAD was 2.5°, 2.7°, and 4.7° with FG, PG, and FH protocols and the difference was again significant between guided and FH protocols (FG vs. FH, $p = 0.000$; PG vs. FH, $p = 0.000$). Maximum GAD was approximately 3° with guided protocols and 5.4° with FH protocol.

Overall, the GAD was lowest in group SM1 as compared to SM2 and SM3 groups with significant difference between SM1 and SM2 and SM1 and SM3 ($p = 0.000$). Combined effect of SM and protocol was significant ($p = 0.000$) on GAD of implants (Table 8 and Figure 10).

4 | Discussion

To the best of our knowledge, this was the first study of its kind where models were digitally designed by altering the positions

TABLE 1 | Mean vertical deviation of implant platform (MVP) within each type of socket morphology (SM) and intergroup comparison after implant placement with different surgical protocols (FH, Freehand; FG, Fully guided; PG, Pilot guided).

Mean vertical deviation of implant platform in millimeters (MVP)											
SM1				SM2			SM3			p	F (p)/two-way ANOVA
	FG	PG	FH	FG	PG	FH	FG	PG	FH	SM1 vs. SM2 = 0.03 SM1 vs. SM3 = 0.13 SM2 vs. SM3 = 0.8	SM = 3.59 (0.03)
Mean ± SD	0.83 ± 0.17	0.86 ± 0.32	1.27 ± 0.27	0.78 ± 0.30	1.11 ± 0.34	1.60 ± 0.32	0.91 ± 0.16	1.18 ± 0.22	1.29 ± 0.29		Protocol = 30.54 (0.000)
p	FG vs. PG = 0.96, FG vs. FH = 0.002, PG vs. FH = 0.000			FG vs. PG = 0.07 FG vs. FH = 0.000 PG vs. FH = 0.006			FG vs. PG = 0.03 FG vs. FH = 0.003 PG vs. FH = 0.56				SM*Protocol = 2.71 (0.04)
p	0.001			0.000			0.003				

Abbreviations: SM1, Socket morphology 1; SM2, Socket morphology 2; SM3, Socket morphology 3.

TABLE 2 | Maximum horizontal deviation of implant platform (MHP) within each type of socket morphology (SM) and intergroup comparison after implant placement with different surgical protocols (FH, Freehand; FG, Fully guided; PG, Pilot guided).

Maximum horizontal deviation of implant platform in millimeters (MHP)											
SM1				SM2			SM3			p	F (p)/two-way ANOVA
	FG	PG	FH	FG	PG	FH	FG	PG	FH	SM1 vs. SM2 = 0.000 SM1 vs. SM3 = 0.68 SM2 vs. SM3 = 0.006	SM = 9.04 (0.000)
Mean ± SD	1.28 ± 0.100	1.21 ± 0.159	1.51 ± 0.35	1.47 ± 0.27	1.61 ± 0.32	1.78 ± 0.37	1.19 ± 0.21	1.40 ± 0.20	1.58 ± 0.33		
p	FG vs. PG = 0.8 FG vs. FH = 0.08 PG vs. FH = 0.02			FG vs. PG = 0.62 FG vs. FH = 0.10 PG vs. FH = 0.47			FG vs. PG = 0.19 FG vs. FH = 0.006 PG vs. FH = 0.27				Protocol = 10.09 (0.000)
p All groups	0.019			0.123			0.008				SM*Protocol = 0.68 (0.61)

Abbreviations: SM1, Socket morphology 1; SM2, Socket morphology 2; SM3, Socket morphology 3.

TABLE 3 | Maximum horizontal deviation of implant apex (MHA) within each type of socket morphology (SM) and intergroup comparison after implant placement with different surgical protocols (FH, Freehand; FG, Fully guided; PG, Pilot guided).

Maximum horizontal deviation of implant apex in millimeters (MHA)											
SM1				SM2			SM3			*p*	*F* (*p*)/two-way ANOVA
	FG	PG	FH	FG	PG	FH	FG	PG	FH	SM1 vs. SM2 = 0.000 SM1 vs. SM3 = 0.000 SM2 vs. SM3 = 0.000	SM = 39.62 (0.000)
Mean ± SD	1.029 ± 0.259	1.021 ± 0.108	1.773 ± 0.704	2.722 ± 0.699	2.418 ± 0.793	2.914 ± 0.736	1.621 ± 0.464	1.948 ± 0.603	2.520 ± 0.760		
p		FG vs. PG = 0.99 FG vs. FH = 0.002 PG vs. FH = 0.002			FG vs. PG = 0.63 FG vs. FH = 0.83 PG vs. FH = 0.31			FG vs. PG = 0.45 FG vs. FH = 0.009 PG vs. FH = 0.12			Protocol = 9.84 (0.000)
p All groups		0.001			0.338			0.011			SM*Protocol = 1.13 (0.35)

Abbreviations: SM1, Socket morphology 1; SM2, Socket morphology 2; SM3, Socket morphology 3.

TABLE 4 | Bucco lingual deviation at platform within each type of socket morphology (SM) and intergroup comparison after implant placement with different surgical protocols (FH, Freehand; FG, Fully guided; PG, Pilot guided).

Bucco lingual variation at platform in millimeters (BLP)											
SM1				SM2			SM3			*p*	*F* (*p*)/two-way ANOVA
	FG	PG	FH	FG	PG	FH	FG	PG	FH	SM1 vs. SM2 = 0.000 SM1 vs. SM3 = 0.000 SM2 vs. SM3 = 0.001	SM = 41.39 (0.000)
Mean ± SD	0.683 ± 0.159	0.636 ± 0.337	0.629 ± 0.024	1.366 ± 0.356	1.248 ± 0.308	1.492 ± 0.407	1.041 ± 0.174	0.876 ± 0.420	1.292 ± 0.273		
p		FG vs. PG = 0.91 FG vs. FH = 0.87 PG vs. FH = 0.99			FG vs. PG = 0.75 FG vs. FH = 0.71 PG vs. FH = 0.3			FG vs. PG = 0.46 FG vs. FH = 0.18 PG vs. FH = 0.01			Protocol = 3.75 (0.03)
p All groups		0.87			0.33			0.018			SM*Protocol = 1.27 (0.29)

Abbreviations: SM1, Socket morphology 1; SM2, Socket morphology 2; SM3, Socket morphology 3.

TABLE 5 | Buccolingual deviation at apex within each type of socket morphology (SM) and intergroup comparison after implant placement with different surgical protocols (FH, Freehand; FG, Fully guided; PG, Pilot guided).

Buccolingual variation at apex in in millimeters (BLA)											
SM1				SM2			SM3			p	F (p)/two-way ANOVA
	FG	PG	FH	FG	PG	FH	FG	PG	FH	SM1 vs. SM2 = 0.000 SM1 vs. SM3 = 0.000 SM2 vs. SM3 = 0.538	SM = 16.61 (0.000)
Mean ± SD	0.714 ± 0.286	0.755 ± 0.361	1.549 ± 0.900	1.714 ± 1.397	1.675 ± 0.615	2.896 ± 0.789	1.451 ± 0.635	1.766 ± 0.711	2.42 ± 0.725		
p		FG vs. PG = 0.98 FG vs. FH = 0.01 PG vs. FH = 0.01			FG vs. PG = 0.99 FG vs. FH = 0.03 PG vs. FH = 0.03			FG vs. PG = 0.01 FG vs. FH = 0.57 PG vs. FH = 0.10			Protocol = 16.61 (0.000)
p All groups		0.005			0.01			0.01			SM*Protocol = 0.42 (0.79)

Abbreviations: SM1, Socket morphology 1; SM2, Socket morphology 2; SM3, Socket morphology 3.

TABLE 6 | Mesiodistal deviation at platform within each type of socket morphology (SM) and intergroup comparison after implant placement with different surgical protocols (FH, Freehand; FG, Fully guided; PG, Pilot guided).

Mesiodistal variation at platform in millimeters (MDP)											
SM1				SM2			SM3			p	F (p)/two-way ANOVA
	FG	PG	FH	FG	PG	FH	FG	PG	FH	SM1 vs. SM2 = 0.24 SM1 vs. SM3 = 0.91 SM2 vs. SM3 = 0.44	SM = 1.42 (0.25)
Mean ± SD	0.859 ± 0.130	0.851 ± 0.339	1.341 ± 0.375	0.898 ± 0.426	0.586 ± 0.414	1.082 ± 0.346	0.791 ± 0.264	0.969 ± 0.477	1.172 ± 0.549		
p		FG vs. PG = 0.99 FG vs. FH = 0.004 PG vs. FH = 0.003			FG vs. PG = 0.20 FG vs. FH = 0.56 PG vs. FH = 0.02			FG vs. PG = 0.65 FG vs. FH = 0.16 PG vs. FH = 0.57			Protocol = 9.38 (0.000)
p All groups		0.001			0.03			0.18			SM*Protocol = 1.25 (0.29)

Abbreviations: SM1, Socket morphology 1; SM2, Socket morphology 2; SM3, Socket morphology 3.

TABLE 7 | Mesiodistal deviation at apex within each type of socket morphology (SM) and intergroup comparison after implant placement with different surgical protocols (FH, Freehand; FG, Fully guided; PG, Pilot guided).

Mesiodistal variation at apex in millimeters (MDA)											
	SM1			SM2			SM3			p	F (p)/two-way ANOVA
	FG	PG	FH	FG	PG	FH	FG	PG	FH		
Mean ± SD	0.505 ± 0.115	0.545 ± 0.245	0.623 ± 0.267	0.449 ± 0.529	0.645 ± 0.483	0.326 ± 0.339	0.671 ± 0.269	0.769 ± 0.238	0.598 ± 0.388	SM1 vs. SM2 = 0.605	SM = 2.75 (0.07)
p		FG vs. PG = 0.91 FG vs. FH = 0.46 PG vs. FH = 0.71			FG vs. PG = 0.61 FG vs. FH = 0.82 PG vs. FH = 0.28			FG vs. PG = 0.75 FG vs. FH = 0.85 PG vs. FH = 0.43		SM1 vs. SM3 = 0.36 SM2 vs. SM3 = 0.05	Protocol = 1.36 (0.26)
p All groups		0.48			0.33			0.46			SM*Protocol = 0.89 (0.47)

Abbreviations: SM1, Socket morphology 1; SM2, Socket morphology 2; SM3, Socket morphology 3.

of the anatomic root of central incisor to simulate the clinical scenario of patients with variable root positions and socket morphologies based on classification of radial root position (Gluckman et al. 2018). This classification was used as it has been stated to be relevant for clinical decision making for anterior IIP. Results showed deviations between planned and actual implant positions within same socket morphology with freehand and guided surgical protocols. Highest implant accuracy was noticed in group SM1 with any protocol. Implant accuracy was also higher with guided than freehand protocol in all socket morphologies. Despite standardized surgical settings, implant planning, designing and printing of the surgical guides, deviations in implant positions were evident in all groups. Since implant accuracy varied among groups and was influenced by class of root position and surgical protocol, the null hypothesis was rejected.

FG protocol was found to be most accurate followed by PG and FH protocols in a recent clinical trial (Lou et al. 2021). Chen et al. (2018) observed lesser mean angular deviation and maximum horizontal deviation of implant and apex after guided anterior IIP as compared to freehand placement. They also reported higher tendency for buccal deviation of implants, especially in FH group. This confirms that deviation in implant position can occur even with guided implant placement, but it is lesser than freehand placement. Deviations in Group SM1 were higher than Groups SM2 and SM3. Hence these factors establish the need of a study with more emphasis on socket morphology and influence of different surgical protocols while planning for an immediate implant.

Within each socket, difference in mean vertical deviation of implant platform (MVP) was significant between guided and FH protocols in all groups with an exception in group SM3 (PG vs. FH $-p = 0.5$). Chen et al. (2018) reported no difference in depth of anterior immediate implants placed with guided and FH protocol (<1 mm, $p = 0.36$). The primary objective of their study was to compare the effect of surgical protocol after implant placement in human cadaveric bone. In another in vitro study, mean vertical deviation was found to be almost twice higher with FH as compared to FG protocol in fresh extraction sockets (Chen et al. 2022). But the deviations in all three groups were in the range of 0.5–1 mm. Higher mean vertical deviation in our study correlates with the results of a previous randomized clinical trial on anterior immediate implants which reported similar vertical deviation of implant platform (PG = 1.04 ± 1.05, FG = 0.90 ± 0.63) with no difference between FG and PG protocol ($p < 0.05$) (Kraft et al. 2020).

Intergroup difference for MVP was significant only between SM1 and SM2 ($p = 0.03$), which may be because of the higher deviation in SM2 with PG or FH protocols. This can be attributed to the surgeon's clinical judgement of thin buccal wall at the crest in SM2 and henceforth, preference of bone augmentation rather than going for a deeper implant placement in similar clinical scenario. Gluckman et al. (2018) reported highest prevalence of Class II root position associated with thin buccal wall (76.5%) and recommended bone grafting due to higher possibility of facial bone resorption with time.

Vertical position of implant platform is usually planned 1–2 mm subcrestal in case of an anterior immediate implant

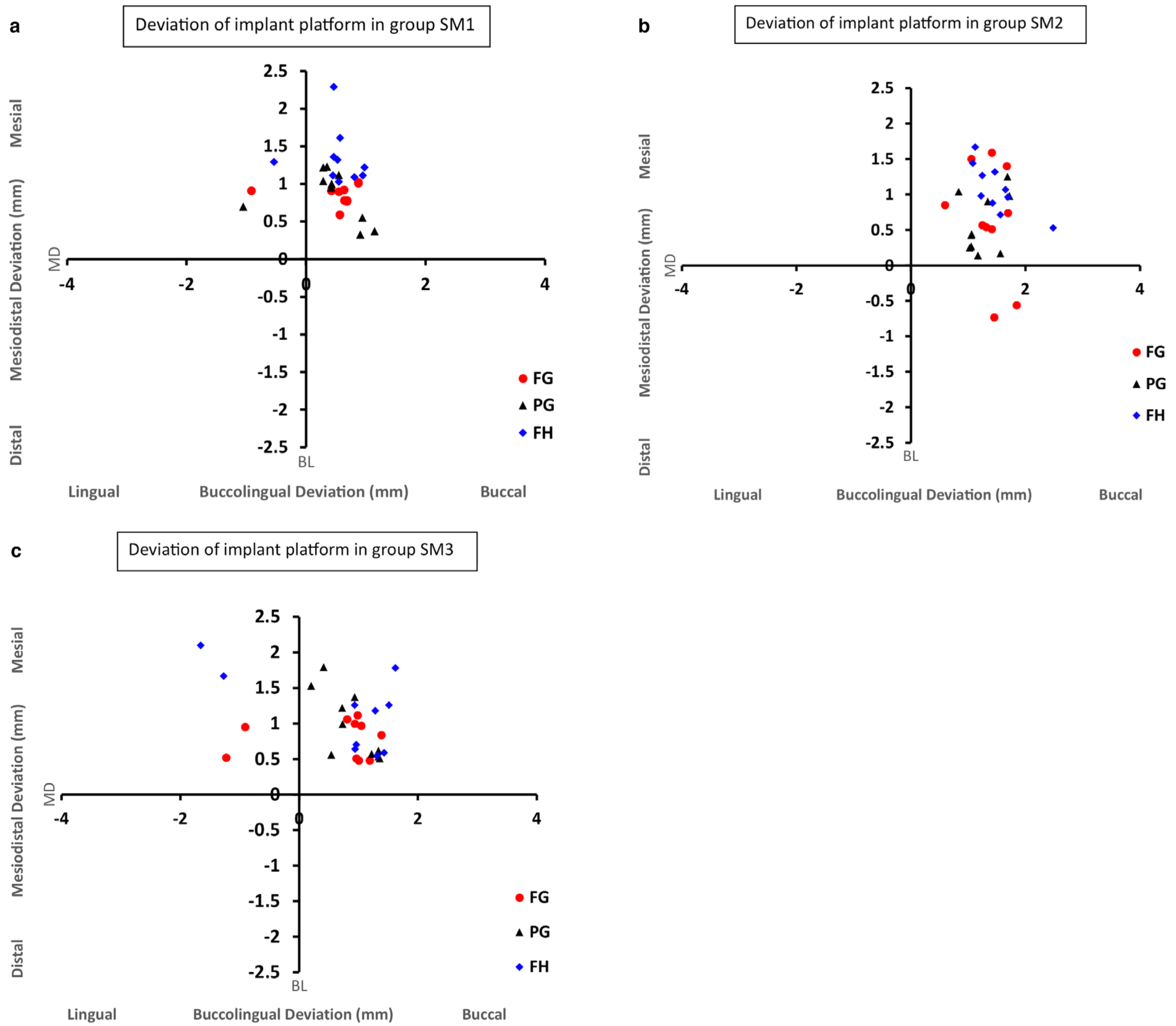

FIGURE 7 | Scatter diagram showing mesiodistal and buccolingual deviation of implant platform in each type of socket morphology (SM): (a) SM1, (b) SM2 (c) SM3.

(Buser et al. 2004; Kraft et al. 2020). Results of this study suggest that socket morphology should be considered along with other clinical factors during virtual planning for vertical position of implant platform. Since there was no soft tissue to mimic the flap as in clinical situation, crestal bone levels and CEJ of adjacent central incisor were taken into consideration to finalize the vertical position of the implant platform. This may be the reason of higher deviation with PG or FH protocols.

Maximum horizontal deviation of implant platform (MHP) and apex (MHA) were lower with guided protocols than FH protocol in all groups. In an earlier study, lesser horizontal deviation of implant platform (0.85 mm) and apex (0.93 mm) were observed after guided anterior IIP in comparison to freehand placement (platform = 1.43 mm, apex = 2.2 mm), with a significant difference between two protocols (Chen et al. 2018). Results of our study showed higher deviations of implant platform (FG = 1.5 mm, FH = 1.8 mm) and apex (FG = 2.7 mm, FH = 3 mm) with respective surgical protocols than those found in abovementioned study. Possible reasons responsible for this difference could be the variance in density of cadaveric bone vs. resin models used in our study or the added effect of socket morphology (Chen et al. 2018).

Kraft et al. (2020) in their clinical study reported MHP as 1.26 mm and 1.34 mm with FG and PG protocols respectively. MHA was reported to be 1.97 and 2.5 mm with FG and PG protocols. Maximum horizontal deviation in this study was highest in group SM2 and least in SM1 irrespective of the surgical protocol. The deviations reported by Kraft et al. were comparable to those observed in group SM1 but lower than SM2 and SM3. Higher deviations in our study may be attributed to the difference in socket morphologies which were not taken into consideration in previous studies. Moreover, there is a large variation among the methods or software used to measure deviations in

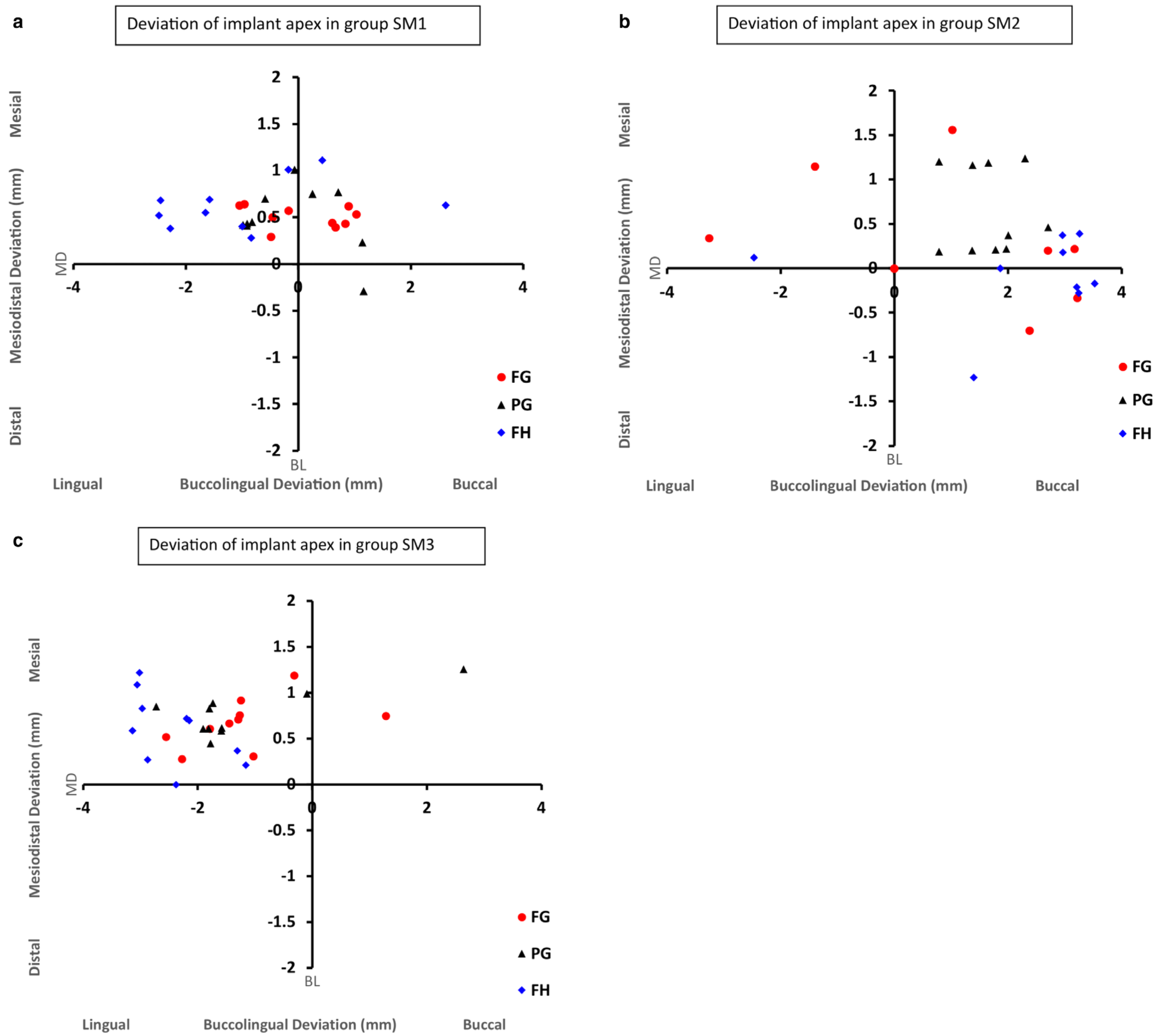

FIGURE 8 | Scatter diagram showing mesiodistal and buccolingual deviation of implant apex in each type of socket morphology (SM), (a) SM1 (b) SM2, (c) SM3.

previous studies (Chen et al. 2020; Hanozin et al. 2022; Kraft et al. 2020; Li et al. 2022).

Similar to the findings of previous studies (Chen et al. 2020; Kraft et al. 2020), no difference was observed between FG and PG protocols and higher deviations of implant apex were observed than the platform in this study (Albiero et al. 2019). Direct visibility at the platform and an intention to engage more of apical bone, might be responsible for more deviation at the apex than at the crest. Higher deviation in SM2 and SM3 may be because the sockets varied significantly in the apical part according to the respective root positions. The osteotomy for an IIP begins after penetrating the palatal wall but the drills may get deflected in their course in the apical part especially with PG or FH protocols. Intraoperative verification at each step and use of clinical judgement even during guided implant placement has been recommended to reduce the probability of error.

Direction of deviation is also a crucial factor to consider especially in the anterior aesthetic zone. In this study, most of the implants showed mesial deviation except few implants in SM2 group showing distal deviation. Chen et al. (2022) measured the direction of deviation but no specific tendency towards mesial or distal deviation of implant platform or apex was found in their study. Hanozin et al. reported nonsignificant effect of mesiodistal deviation on clinical outcome after IIP with freehand or computer-assisted protocol but they recommended a safety zone of at least 2 mm to avoid encroachment of vital anatomical structures or roots of adjacent teeth (Cassetta et al. 2014; Hanozin et al. 2022). Proximal deviation might be reflected as interference and difficult seating of the prefabricated provisional crown.

B-L deviation of implant platform and apex varied among different socket morphologies. The direction of deviation did

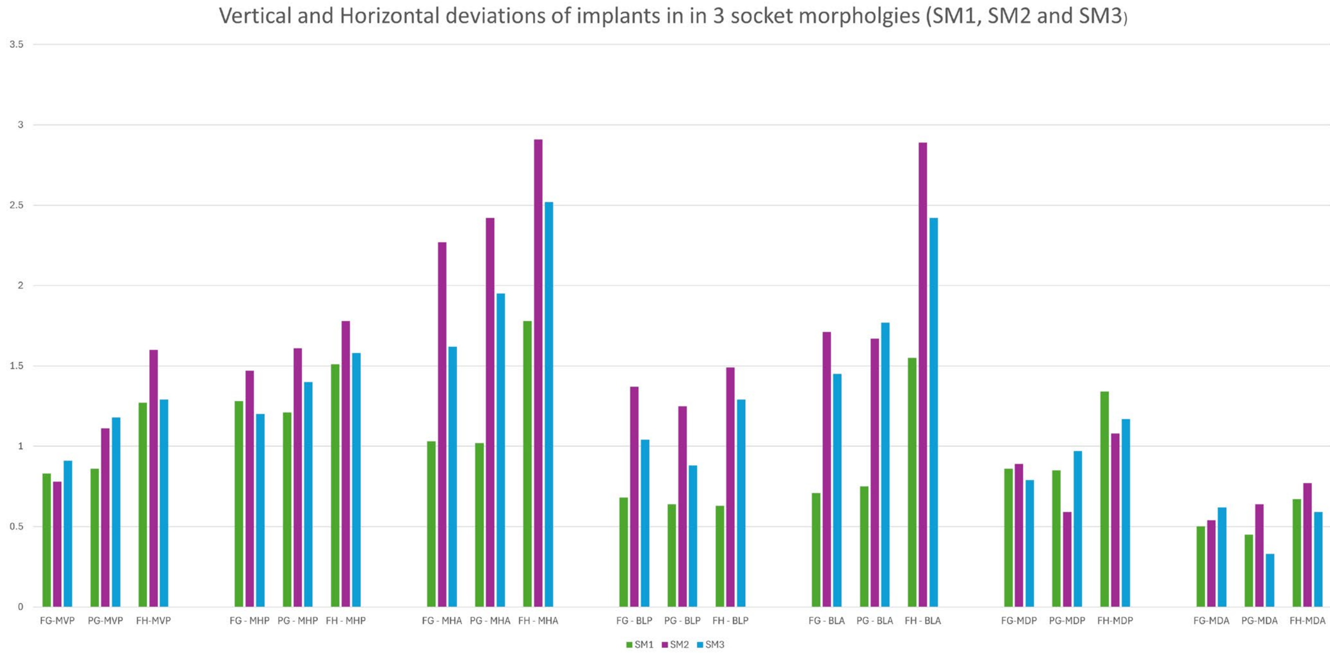

FIGURE 9 | Graphical representation of horizontal deviations in all groups: BLA, buccolingual deviation of implant apex; BLP, buccolingual deviation of implant platform; MDA, mesiodistal deviation of implant apex; MDP, mesiodistal deviation of implant platform; MHA, maximum horizontal deviation of implant apex; MHP, maximum horizontal deviation of implant platform; MVP, Mean vertical deviation.

correlate directly with the root position in the socket. In SM1, root is centrally placed with its long axis parallel to the walls of the alveolar housing. In SM2, root is in close approximation with the buccal wall with long axis of the tooth in retroclined position while in SM3; the apex of the root is towards the palatal wall owing to the proclined inclination of its long axis. B-L deviations were higher at apex than at platform in all groups which is similar to findings of a previous study (Chen et al. 2022). Higher tendency of buccolingual deviation in anterior immediate implant has also been reported earlier (Koticha et al. 2012). Reason can be attributed to the buccal gap owing to the mismatch between implant shape and socket morphology and hence, slipping of drill into the path of least resistance (Chen et al. 2018). For screw-retained prosthesis with palatal access, surgeons do attempt to keep the drills close to the palatal wall, which might be possible for lesser buccal deviation at platform than at the apex (Kraft et al. 2020).

Selection of a longer guide sleeve, keeping lesser distance between the sleeve and the bone are few factors which can be considered while designing of surgical guides to control the deviation of implant in buccolingual direction (van Assche and Quirynen 2010). As studies have reported higher deviation with FH protocol as compared to the guided protocol, osteotomy can be initiated with penetration of the palatal wall with a round bur before pilot drilling. These steps might provide better stabilization of sequential drills and hence, lesser buccal deviation. Effect of class of root position was significant on buccolingual deviation of implants. Therefore, direction of previous root should be kept in mind to maintain a controlled implant insertion, with an overall preference of guided protocols than freehand placement (Chen et al. 2018).

In this study, with FG and PG protocol, SM2 showed highest GAD among groups, while with FH protocol, highest deviation was in SM3 group. Hanozin et al. reported a statistically significant difference and three times higher mean angular deviation in implants placed with FH protocol as compared to those placed with FG protocol (Hanozin et al. 2022). But their results were mainly based on implants placed in healed maxillary sites. Chen et al. reported lesser mean angular deviation after guided anterior IIP as compared to freehand placement (Chen et al. 2018). All implant placement protocols led to lowest deviation in SM1 as compared to SM2 and SM3, though the mean values were within the limits being reported in above studies.

Earlier literature has recommended safety margin of 1–2 mm in horizontal direction and up to 5° of angular deviation when planning for implants with FG protocol (Bover-Ramos et al. 2018; Tahmaseb et al. 2018). In his study, mean BLP was highest in SM2 (1.5 mm approximately) and BLA was between 1.5–3 mm in SM2 and SM3 groups. GAD was approximately 4°–5° in SM2 and SM3 with PG or FH protocols. Combined effect of angular and buccolingual deviations can compromise the optimal 3-dimensional implant position along with the encroachment of buccal gap. Narrow buccal gap (≤ 2 mm) around immediate implant has been found to decrease buccal bone thickness with time (Levine et al. 2022). Immediate implant placement in SM2 and SM3 warrant caution, especially when they are associated with thin buccal wall. Gluckman et al. (2018) reported average bone thickness of 0.8 mm in maxillary central incisor region and 88% sockets with type 2 and 3 root positions. They recommended a delayed implant placement protocol in such clinical scenarios. Many authors have recommended maintaining a wider buccal gap and filling it with a suitable graft material to enhance

TABLE 8 | Global angular deviation (GAD) within each type of socket morphology (SM) and intergroup comparison after implant placement with different surgical protocols (FH, Freehand; FG, Fully guided; PG, Pilot guided).

Global angular deviation in degrees (GAD)	SM1			SM2			SM3			p	F (p)/two-way ANOVA
	FG	PG	FH	FG	PG	FH	FG	PG	FH		
Mean ± SD	1.92 ± 0.537	2.213 ± 0.394	2.38 ± 0.765	3.104 ± 0.469	2.896 ± 0.528	4.204 ± 0.718	2.517 ± 0.213	2.732 ± 0.259	4.773 ± 0.540	SM1 vs. SM2 = 0.000 SM1 vs. SM3 = 0.000 SM2 vs. SM3 = 0.89	SM = 52.82 (0.000)
p		FG vs. PG = 0.53 FG vs. FH = 0.21 PG vs. FH = 0.80			FG vs. PG = 0.70 FG vs. FH = 0.001 PG vs. FH = 0.000			FG vs. PG = 0.40 FG vs. FH = 0.000 PG vs. FH = 0.000			Protocol = 55.05 (0.000)
p All groups		0.238			0.000			0.000			SM*Protocol = 11.03 (0.000)

Abbreviations: SM1, Socket morphology 1; SM2, Socket morphology 2; SM3, Socket morphology 3.

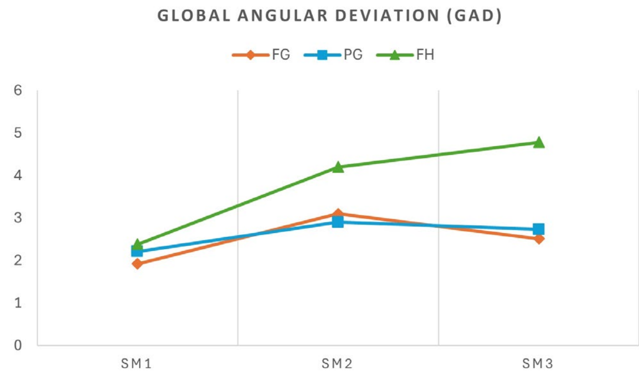

FIGURE 10 | Graphical representation of global angular deviations in all groups.

long term health of hard and soft tissues (Levine et al. 2022; Pluemsakunthai et al. 2015; Seyssens et al. 2022).

Main effect of surgical protocol was significant on all variables with an exception of mesiodistal deviation. Deviations between actual and planned implant positions were observed within each group even with the guided surgical protocols (FG or PG). Guided implant placement can lead to a predictable accuracy in implant position but not an absolute accuracy. This is attributed to conglomeration of errors at different steps from planning to actual implant placement and can be higher in clinical settings as compared to in vitro studies (Abduo and Lau 2020).

All the surgical guides were stable on the models during the implant surgery but there could be the inherent errors in the guides. For anterior implants, longer drills are required for guided implant placement. This can increase the tolerance within the sleeves and increase the possibility of error. The inherent gap between the key and the sleeve, may also lead to movements while drilling through the guide (Raabe et al. 2023; Schneider et al. 2015). Raabe et al. (2023) suggested use of sleeveless guide-hole design to overcome this problem and achieve higher accuracy in implant position.

Errors and variations due to surgical protocol can also be attributed to the difference in the accessibility and visibility of the surgical site. Direct visibility of the surgical site is limited in FG protocol. So, it is difficult to assess the error or perform any intraoperative manipulation. While with PG protocol, adjustments are possible after pilot drilling according to surgeon's clinical judgement. Guides with closed sleeves don't allow for change in direction of drill which is possible with FH or with subsequent drills in PG protocol (Raabe et al. 2023). Even if surgeon is aware of socket morphology, change in direction of drilling is not possible. When drills reach the palatal bone plate, a small angle between the drill and bony wall may cause the drill to slide buccally (Li et al. 2022). Therefore, surgeon's experience and skill of implant placement is of paramount importance to achieve acceptable implant accuracy especially with freehand surgeries (Hanozin et al. 2022). Moreover, intraoperative verification with a radiograph is recommended to check the direction of osteotomy before final implant placement.

This in vitro study was done under ideal settings with every attempt to simulate clinical conditions and surgeon was aware of difference in socket morphologies during implant placement. But there are certain crucial clinical factors like difference in density of bone vs. resin, thickness of labial bone, proximity to vital structures, gingival phenotype, and different inclinations of antagonists, which could not be replicated in this study. The outcome may be different in actual clinical settings and without prior consideration of socket morphology. In this study, only implant accuracy was analyzed, while future studies reporting on the implications of accuracy on seating of immediate provisional crown may help to make these result clinically relevant. Future randomized clinical trials with primary focus on effect of different socket morphologies on the accuracy of implant, biological factors like buccal bone thickness and prosthetic outcomes will help to better extrapolate the results of this study.

5 | Conclusions

Within the limitations of this in vitro study, following conclusions were drawn:

1. Despite of same implant planning, significant deviations in actual implant positions were observed in all socket morphologies. Highest implant accuracy was observed in sockets with a central root position (SM1) while it was least in sockets with a retroclined root position (SM2), irrespective of the surgical protocol.
2. Effect of socket morphology was significant on all variables except for mesiodistal deviation.
3. Within each socket, higher implant accuracy was observed with guided protocols than freehand protocol. Hence, guided protocols may be preferred over freehand implant placement in fresh extraction sockets of the maxillary central incisor.

Author Contributions

G.P., R.J., and J.A. conceived the ideas. L.N., G.P., and A.G. collected the data. J.A. analyzed the data. G.P., J.A., and R.J. led the writing. Final manuscript was approved by all authors.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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