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Influence of Kennedy class and number of implants on the accuracy of dynamic implant navigation: An in vitro study using an X-ray free evaluation methodology

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ABSTRACT

Objectives: The aim of this in vitro study was to evaluate the accuracy of fully guided dynamic implant navigation surgery in Kennedy I, II, and III class dental arch defects with two different implant designs, using an X-ray free evaluation method.
Methods: Polyurethane resin maxillary models simulated posterior edentulous defects. Four cone beam computed tomography (CBCT) scans and four intraoral (IOS) scans were obtained for each model and a digital wax-up with the correct implant positions was made. The accuracy of implant positions was evaluated using an IOS-based X-ray-free method (3Shape). Four deviation characteristics were evaluated: insertion point, depth deviation, horizontal and angle deviation.
Results: The insertion point deviation measures ranged from 0.19 mm to 1.71 mm. Depth (s) and (u) deviations ranged from -1.47 mm to 0.74 mm and from 0.02 mm to 1.47 mm, respectively. Horizontal deviation ranged from 0.09 mm to 1.37 mm.
Conclusions: There is a tendency of a decreasing insertion point deviation for an increasing number and distribution area of the teeth (increasing Kennedy class number). Kennedy class II and distal implant position had the most influence for the higher deviations.
Clinical significance: Dynamic implant guidance provides accurate spacing, angulation, depth and position of the implants. It is important to understand how the number of missing teeth and implant design could influence the accuracy of dynamic implant navigation. Thus, it is important to evaluate factors influencing the accuracy of dynamic systems by using a X-ray-free post-operative method and to overcome the limitations of providing multiple CBCT scans.

1. Introduction

Guided implant dentistry has increasingly become a common tool for patient safety and prosthetically accurate implant positioning. Guided implant placement has been proven to be more accurate compared to free-hand surgery [1–4]. There are two main guidance methods: static and dynamic navigation. The first method is based on a 3D printed surgical template.The second method uses real-time drill tracking (typically on a screen) using the patients' cone beam computed tomography scan (CBCT) [5,6]. Both of these options are available for fully guided as well as flapless implant surgery.

Dynamic implant guidance has its advantages and limitations. Dynamic navigation takes less preparation time than static guides, as there is no need for guide fabrication (a single visit approach is possible for planning and surgery). In addition, it is much more flexible and allows the surgeon to make intraoperative changes according to the situation

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[7]. Furthermore, it also eliminates specific static guide-related issues, such as limited field visibility, lack of drilling irrigation, and guide breakage [8–10]. Another advantage of the dynamic guidance is that it does not require a separate drill set and is less challenging for patients with limited mouth opening (especially in posterior regions) [8].

The main limitations of dynamic guided methods are the high cost of the system and the learning curve [7,11,12]. Also, fully edentulous arches are still challenging cases, with this method requiring additional interventions and increasing costs (such as mini-implant placement before the main surgery) [8,11].

Recent systematic reviews have shown the accuracy of dynamic navigation to be similar to static guided surgery [3,13,14]. Unlike static guides, dynamic navigation systems show no difference comparing in vitro and clinical accuracy [13,14]. However, higher heterogeneity and a lack of clinical data on dynamic guidance accuracy exist [13]. Thus, it is important to evaluate factors influencing the accuracy of dynamic systems.

Schnutenhaus et al. have noted that most studies vary according to influencing factors in their design: fundamental differences in dynamic tracking systems, implant planning programs and implant systems [13].

Most studies evaluating the accuracy of dynamic implant placement use post-operative CBCT [13–15]. The method uses a plan (pre-operative CBCT scan with planned implant positions) being superimposed with post-operative CBCT with actual implant positions. This method has its limitations. The main drawback is the need for additional patient exposure to ionising radiation (X-rays), which has little clinical reasoning and applicability. This was also noticed in recent literature reviews, and X-ray-free methods were proposed [14,16]. It is also of serious concern as a significant proportion of the clinical studies evaluating guided surgery fail to report the approval of ethical committees [17]. The other challenge is that CBCT scan accuracy is limited by the voxel size [18,19] as well as other settings (kVp, mA) [20]. Post-operative implant image, in most cases, is not precise in CBCT scan due to metal-related scattering, artefacts and other distortions [21,22]. The last but not least important aspect is that using this method, a researcher places a generic digital implant shape over an x-ray volume. This approach raises questions regarding its limitations when reporting accuracy. All these challenges suggest looking for a safer and less human error-sensitive method for the implant position comparing and accuracy evaluation.

Authors reveal that the accuracy of implant angulation and positioning is the leading advantage of dynamic implant navigation when compared to guided or free-hand implant surgery [23–25]. During the procedure the implants are placed in a pre-planned, prosthetic-driven position with a consideration on the crucial anatomical structures [26]. The implant design should also be considered an important variable [27]. Currently, there are quite some studies evaluating the accuracy of guided implantation (both static and dynamic), but the impact of implant design is not discussed, however from the point of clinical practice, different implant designs and thus different drilling sequences lead to variable implant bed preparation, which can affect the accuracy of a fully guided implantation. Furthermore, there is a lack of data on how the number of missing teeth and implant design could influence the accuracy of dynamic implant navigation.

This model study evaluated the accuracy of fully guided dynamic implant navigation surgery in Kennedy I (bilateral edentulous posterior defect), Kennedy II (a one-sided, posterior edentulous defect), and Kennedy III (unilateral bounded posterior defect) class dental arch defects with two different implant designs. The study's null hypothesis was that the accuracy is not influenced by the Kennedy class of the edentulous defect, implant position and dental implant design.

2. Material and methods

Polyurethane resin (Modralit® 3 K Set, Dreve Dentamid GmbH, Unna, Germany) maxillary models were fabricated, imitating bone type I (Lekholm & Zarb) [28]. Radiopacity was adjusted by the addition of $BaSO_4$ (Barium sulfate 97% 1–4 μm powder, Alfa Aesar, ThermoFisher (Kandel) GmbH, Germany) to approximate human CBCT by mean area Hounsfield units. The soft tissue component was emulated by silicon gingiva (frasaco GmbH, Tettnang, Germany). The models simulated posterior edentulous defects which need to be restored with two-implant-supported fixed partial dentures. Also, a single molar edentulous defect for an implant-supported crown restoration was also included as a sub-group. Three types of models used in the study were as follows (Fig. 1):

- **Kennedy I (K1)** - bilateral posterior edentulous defects/areas missing molars and premolars (FDI teeth numbers: 17, 16, 15, 14 and 24, 25, 26, 27).
- **Kenndy II (K2)** - unilateral posterior edentulous defect/area missing right side molars and premolars (FDI teeth numbers: 17, 16, 15, 14).
- **Kennedy III (K3)** - two posterior defects:
  a) Left side edentulous defect (Kennedy3) missing both premolars and first molar (FDI numbers: 24, 25, 26).
  b) Single tooth edentulous defect on the right side missing first molar (FDI number 16).

Sample size was calculated using G*Power 3.1 (Heinrich-Heine Universität, Düsseldorf, Germany). The angular deviation was selected as the primary outcome variable. A total sample size of 72 was selected, considering a power of 0.80, an alpha error of 5% and an f2 effect size of 0.4, based on previous studies [29,30].

Four computed cone beam tomography (CBCT) scans (KaVo OP3D, KaVo Dental, Biberach an der Riss, Germany) and four intraoral (IOS) scans (Trios4, 3Shape, Copenhagen, Denmark) were obtained for each model. CBCT scans were performed using a voxel size of 0.2 mm. Each CBCT scan was coded and randomly paired with one of the four IOS scans from the same model group. Each pair of CBCT and IOS was used to create a digital implantation plan, resulting in 4 plans for each model. Planning was performed using SMOP software (Swissmeda AG, Baar, Switzerland): a trained planner (H.P.) made a digital wax-up and positioned implants according to the standard implant placement requirements (confirmed virtually by the dentist):

- Prosthetically driven implant position with screw access hole in the central fossa of the crown;
- Minimal distance between the implant and adjacent tooth was 1,5 mm;
- Minimal distance between adjacent implants was 3 mm;
- Minimal distance from a buccal/lingual wall of a resin model was 1,5 mm;
- Implants placed 1 mm subcrestally;
- 0° angulation between implants supporting FPD.

The length and diameter of the implants were selected according to the standard anatomical situation and occlusal load in premolar and molar areas. For the premolar and molar regions 3.8 mm diameter, 11 mm length and 4.3 mm diameter, 13 mm length implants were selected and planned, respectively (Camlog Biotechnologies AG, Basel, Switzerland). (Table 1)

Each plan was randomly assigned to one of the implant design groups: slightly conical self-tapping design (CONELOG screw-line, Camlog Biotechnologies AG, Basel, Switzerland) (SL group) and a more aggressive conical self-tapping design (CONELOG progressive-line, Camlog Biotechnologies AG) (PL group). This random distribution resulted in 4 implant plans per model case, exported as Standard Tessellation Language (STL) files. Implant bed preparation differed and followed the complete dense bone drilling sequence proposed by the manufacturer for each implant design individually. Repetitions were made using same materials.

Navident system (ClaroNav Inc., Toronto, Ontario, Canada) was used

K1 K2 K3

Fig. 1. Models used in the study.

Table 1
Implant parameters used in the study. CONELOG screw-line and progressive-line implant systems were used (Camlog Biotechnologies AG, Basel, Switzerland).

Position (FDI number)	Diameter	Length	Parallel
Kennedy I			
First premolar (#14)	3.8 mm	11 mm	Yes
Second molar (#17)	4.3 mm	13 mm	Yes
Kennedy II			
First premolar (#14)	3.8 mm	11 mm	Yes
Second molar (#17)	4.3 mm	13 mm	Yes
Kennedy III			
First premolar (#24)	3.8 mm	11 mm	Yes
First molar (#26)	4.3 mm	13 mm	Yes
Single			
First molar (#16)	4.3 mm	13 mm	n/a

for dynamic implant navigation. Each model was placed into a phantom head (ClaroNav Inc.), imitating a real operative situation. A Navident head tracker and a standard trace registration protocol were implemented following the manufacturer's recommendations [31].

Post-operative implant position accuracy was evaluated using an IOS-based X-ray-free method (3Shape). Implant scan bodies were mounted on implants immediately after insertion, and registrations with IOS were taken (3Shape TRIOS 4). The 3Shape software digital scan body was aligned using a 3-point method (Fig. 2), and the post-operative implant position coordinates were received.

Afterwards, using the same software, pre-operative (planned) and post-operative implant positions were compared, and five deviation characteristics were evaluated:

- **Insertion point** - the distance between the centre points of the platforms of the two implants is the displacement measure. (Fig. 3A)
- **Depth (s)** - depth deviation (signed values) shows the vertical deviation of the implant compared to the planned implant position. This is calculated by projecting the measured implant's centre to the planned implant's centre. In Fig. 3B, the axes for the implants are marked in blue, and the projected insertion point is the additional orange dot, placed using the dotted yellow line. The depth error is the distance marked by the full yellow line. It is negative if the placed implant is deeper than the planned implant. Otherwise, it is positive.
- **Depth (u)** - depth deviation (unsigned values).
- **Horizontal deviation**. It is calculated by finding the shortest distance between the centre of the planned implant to the axis of the placed one. This is the distance between the top two orange dots in Fig. 3C.
- **Angle deviation**. It is calculated in degrees by finding the smallest angle between the two implant centre axes, and this angle is marked in yellow in Fig. 3D.

Statistical analysis was performed using R i386 4.0.5 software (R software, University of Auckland, New Zealand). The graphs were plotted using the "ggplot2″ package. To identify statistically significant differences, data normality was tested (Shapiro-Wilk test) and parametric methods (*t*-test, factorial ANOVA with post-hoc contrasts test) were used in case of normal data distribution ("emmeans" package). The level of statistical significance was set at $P<0.05$.

3. Results

The insertion point deviation measures ranged from 0.19 mm to 1.71 mm. Depth (s) and (u) deviations ranged from −1.47 mm to 0.74 mm and from 0.02 mm to 1.47 mm, respectively. Horizontal deviation ranged from 0.09 mm to 1.37 mm. Angle deviations were in the range between 0.36° and 6.17° Mean values and standard deviations according to Kennedy's classification of an edentulous defect and implant design are presented in Table 2. Further statistical analysis (factorial ANOVA) for each deviation type included Kennedy class, implant design and implant position (mesial/distal) as factors. Insertion point, depth (s) and (u), horizontal and angle deviation means and standard deviations for each Kennedy class defect, implant design and mesial/distal implant position are presented in Figs. 4–8, respectively. Statistically significant factorial ANOVA (except for the single tooth edentulous defect) results between the groups are presented in brackets over the bars. Single tooth edentulous defect group means between different implant design groups were compared using a *t*-test (only for the signed depth deviation a significant difference between groups is reported – Fig. 5). In case of a

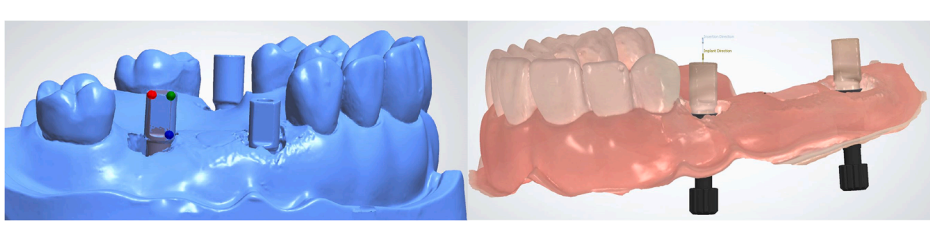

Fig. 2. A three point alignment method used for the alignment of a digital scan body in the software (3shape).

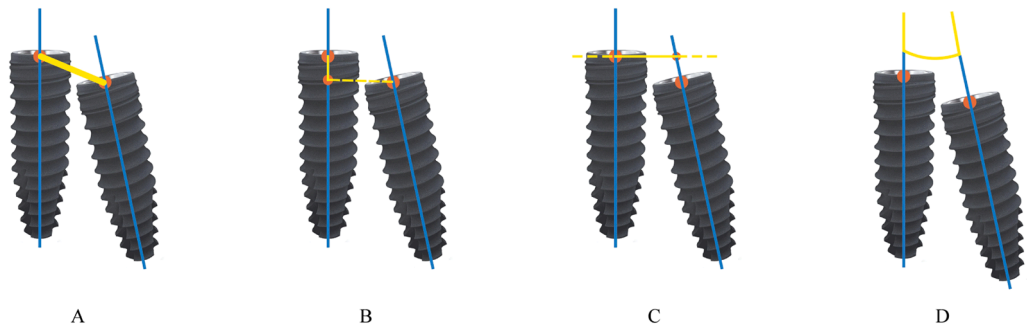

Fig. 3. Deviations measured in the study. A -insertion point; B – depth; C – horizontal; D – angle. The implant image on the left of each figure represents the planned implant position, and the image on the right – represents the post-operative implant position being evaluated.

Table 2
Implant placement deviations according to the edentulous defect Kennedy class and implant design (means ± SDS in mm).

	Insertion point	Depth (s)	Depth (u)	Horizontal	Angle
Kennedy I					
Screw-Line	1.0 ± 0.3	−0.6 ± 0.5	0.6 ± 0.5	0.7 ± 0.3	1.8 ± 0.8
Progressive-Line	0.8 ± 0.4	−0.4 ± 0.7	0.6 ± 0.4	0.5 ± 0.2	2.4 ± 1.0
Kennedy II					
Screw-Line	0.9 ± 0.3	−0.1 ± 0.4	0.3 ± 0.3	0.7 ± 0.4	2.5 ± 1.4
Progressive-Line	0.8 ± 0.4	−0.3 ± 0.6	0.5 ± 0.4	0.63 ± 0.3	3.6 ± 1.6
Kennedy III					
Screw-Line	0.6 ± 0.3	−0.3 ± 0.3	0.4 ± 0.2	0.4 ± 0.3	2.0 ± 1.2
Progressive-Line	0.8 ± 0.4	- 0.2 ± 0.6	0.5 ± 0.4	0.5 ± 0.3	1.9 ± 0.6
Single					
Screw-Line	0.7 ± 0.3	−0.5 ± 0.4	0.5 ± 0.3	0.5 ± 0.2	1.0 ± 0.5
Progressive-Line	0.7 ± 0.3	0.01 ± 0.3	0.2 ± 0.2	0.6 ± 0.3	2.0 ± 1.3

statistically significant difference, bracketed notation is provided in the figures.

Factorial ANOVA of the insertion point data showed statistical significance for the implant design and implant position factors interaction ($p = 0.018$); post-hoc analysis showed a statistically significant difference for the SL design implant comparing mesial and distal implant positions ($p = 0.02$). Kennedy's class in the factorial ANOVA was near a statistical significance level ($p = 0.08$).

Factorial ANOVA of the depth (s) deviation data showed statistical significance for the implant design and implant position factors interaction ($p = 0.02$); post-hoc analysis showed a statistically significant difference for the PL design implant comparing mesial and distal implant positions ($p = 0.05$).

Factorial ANOVA of the depth (u) deviation data showed statistical significance for the implant design and implant position factors interaction ($p = 0.018$); post-hoc analysis showed implant design to have a p-value near statistical significance ($p = 0.07$) in a mesial implant position. The Kennedy class in the factorial ANOVA was near a statistical significance level ($p = 0.07$). T-test analysis for a single tooth edentulous defect showed no statistically significant difference between implant design groups.

Factorial ANOVA of the horizontal deviation data showed statistical significance for the implant position factor ($p = 0.017$). Kennedy class in the factorial ANOVA was near a statistical significance level ($p = 0.066$) and Kennedy class and implant design interaction ($p = 0.07$).

Factorial ANOVA of the angle deviation data showed statistical significance for every factor individually and interactions for the Kennedy class of the edentulous defect and implant position ($p = 0.0008$) and all three factors ($p = 0.013$). K2 class had significantly (post-hoc contrasts test (p-values adjusted using mvt* method)) higher deviation 3.1 ± 1.6° compared to K1 (2.1 ± 1.0°, $p = 0.001$) and K3 class (2 ± 0.9°, $p = 0.0004$) defects. The average deviations for SL and PL implant design groups were 2.1 ± 1.2 and 2.6 ± 1.3°, respectively ($p = 0.0243$). The average deviations for implant positions were: 1.9 ± 1.0° for mesial; 2.8 ± 1.3° for distal ($p = 0.0001$). The Kennedy class of the edentulous

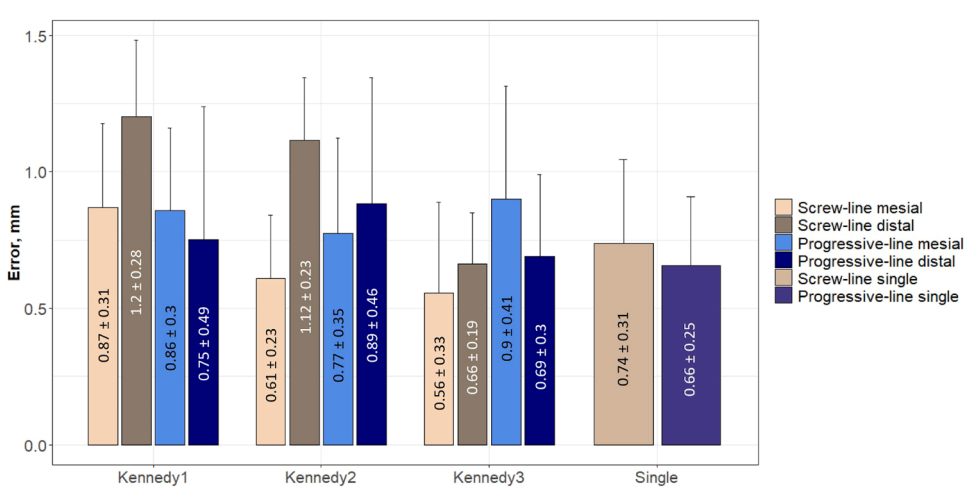

Fig. 4. Insertion point deviation means and standard deviations according to the Kennedy class of an edentulous defect, implant design and implant position (mesial or distal).

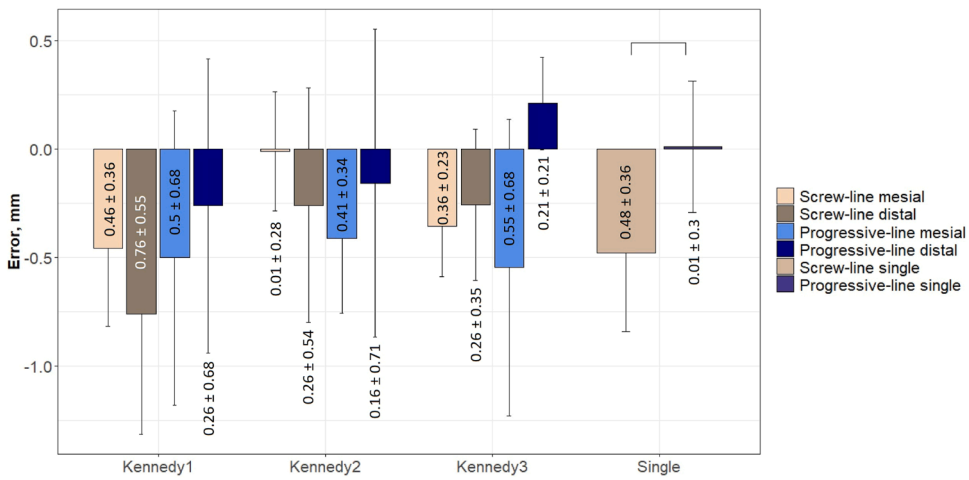

Fig. 5. Signed depth (depth (s)) deviation averages and standard deviations according to the Kennedy class of an edentulous defect, implant design and implant position (mesial or distal). T-test statistics were used for a single tooth edentulous defect case two implant design group comparison ($p = 0.029$).

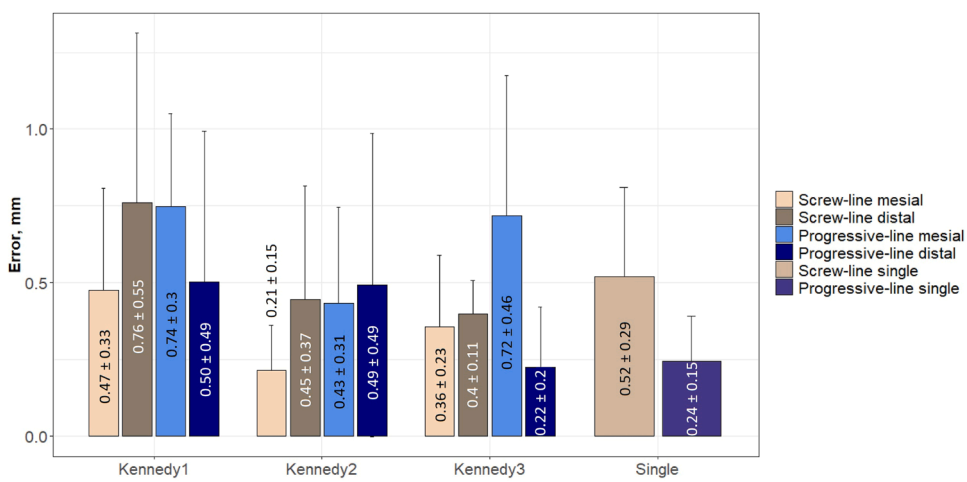

Fig. 6. Unsigned depth (depth (u)) deviation averages and standard deviations according to the Kennedy class of an edentulous defect, implant design and implant position (mesial or distal).

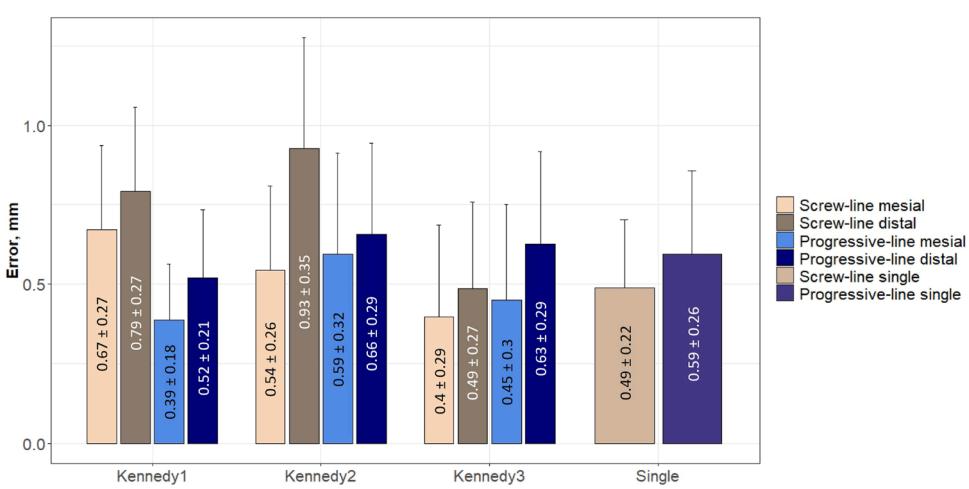

Fig. 7. Horizontal deviation averages and standard deviations according to the Kennedy class of an edentulous defect, implant design and implant position (mesial or distal).

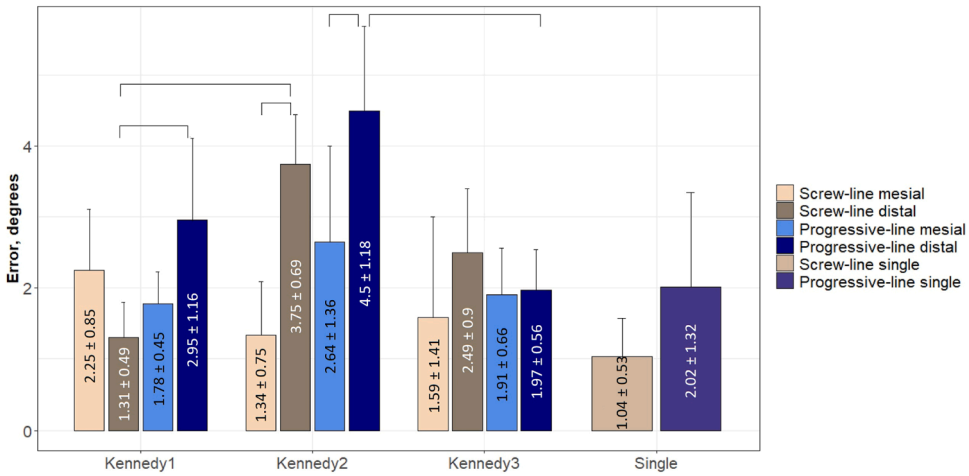

Fig. 8. Angle deviation averages and standard deviations according to the Kennedy class of an edentulous defect, implant design and implant position (mesial or distal). Multiway ANOVA with post-hoc contrasts test (p-values adjusted using mvt* method). *Monte-Carlo corrected p-value based on multivariate normal *t*-test distribution.

defect and implant position interaction showed significant differences (all p values <0.001) and are presented in Fig. 8.

4. Discussion

This study aimed to evaluate the accuracy and influencing factors of dynamic guidance in a maxillary model study. As the vast majority of the other accuracy studies use CBCT based before and after comparison methods, as mentioned in the introduction, it is important to keep in mind this aspect when comparing the results of the current study.

This study's insertion point deviation averages are within a range of published data of a dynamic guidance implant placement: 0.37–1.58 mm for in vitro studies and 0.67–1.37 mm for clinical studies [3,13,14]. The overall insertion point 3D deviation averages ranged between 0.56 ± 0.33 (K3, SL, mesial) and 1.2 ± 0.28 mm (K1, SL, distal) for different subgroups. The data shows a tendency, near statistical significance, of a decreasing insertion point deviation for an increasing number and distribution area of the teeth (increasing Kennedy class number). The latter could be explained by a larger teeth surface area available and a higher spread of the reference points leading to a more accurate trace registration via teeth. Trace registration maps a CBCT scan to a real situation (in this study - a model) via the special tags (tracers). Part of dynamic guidance accuracy studies report a higher insertion point accuracy compared to current study: 0.38 ± 0.25 mm [32], 0.41 ± 0.12 mm [33]. These studies use specific objects (fiducials) for the initial CBCT and trace registration instead of teeth surfaces [32,33]. This suggests that fiducials increase accuracy and reproducibility, but on the other hand, this method is less clinically versatile and has limitations. Contrastingly, Jorba-Garcia et al. (2019) reported slightly higher insertion point deviations using fiducials for trace registration in a Kennedy III class mandibular model study: for the novice - 1.39 ± 0.48 mm, and for an experienced surgeon - 1.19 ± 0.45 mm [31]. In the later study, the authors explain that acrylic splints for the fiducials tend to deform, thus introducing more inaccuracies and showing possible limitations.

Furthermore, in the current study, the SL implant design group's distal implant position showed a significantly higher deviation than the mesial one, which was more evident in K1 and K2 cases; the deviation difference was distal-mesial, being 0.3 mm and 0.5 mm, respectively. However, these tendencies were not observed for PL design implants. Area-related differences were also rejected in a study by Kim et al. (2015): a total of 110 implants (slightly conical design; 4.0 mm x 10 mm) were placed in 11 sites of 10 models using dynamic guidance and found no significant differences between the models and/or the sites [33]. Other studies, having implants placed in different areas, do not provide any statistical analysis regarding this aspect due to study design limitations [32,34]. Guzmán et al. (2019) placed 20 implants (conical design, 4.6 mm × 12 mm) in teeth areas #24 and #26 (K 3 class; 10 implants in each area) using dynamic guidance and found an insertion point deviation of 0.85 ± 0.48 mm [34]. This study design and the results are similar to current findings for the K3 PL group (0.8 ± 0.36 mm) [34]. Finally, Pellegrino et al. (2020) reported high insertion point deviations for fully edentulous maxillary extra-hard models study: 1.55 ± 1.08 mm (experienced) and 1.74 ± 0.64 mm (novice) [35]. The latter study findings suggest that fully edentulous and hard bone cases might influence higher deviations. In the current study, a hard bone (D1) was also simulated; thus, it could be related to higher deviations than in other studies. A 3D insertion point deviation is directly related to depth and horizontal deviations. Therefore, these deviations will be discussed separately to understand better the factors influencing insertion point accuracy.

Depth (u) deviation averages for various subgroups ranged from 0.21 ± 0.15 mm to 0.76 ± 0.55 mm. These findings are similar to data provided by systematic reviews for in vitro studies: 0.26–1.14 mm [3,13]. Differences in implant and drill design could influence statistically significant lower deviations for mesial implants in the SL group compared to the PL group. PL implant, by a rotation step of 120°, changes its depth by 0.3 mm compared to 0.2 mm in SL implants. For the SL group, there was a tendency for a lower mesial implant deviation compared with distal (more evident in K1 and K2 situations), which might be related to trace registration accuracy via teeth. However, there was no such tendency for the PL group. In addition, PL mesial implant deviations tended to be higher than distal, with a high deviation (0.72 ± 0.46 mm) in K3 class for PL mesial implant (3.8 × 11 mm). Similar data was also reported by Kang et al. (2014), showing higher depth deviations in the fully edentulous mandible model for the canine region (1.14 ± 1.25 mm) compared to the molar region (0.76 ± 0.84 mm) [36]. These tendencies could be better explained by analysing depth (s) data.

Horizontal deviations ranged from 0.39 ± 0.18 to 0.93 ± 0.35 mm for various subgroups. These findings are within the range of other studies: 0.36–1.27 mm [3] and 0.33–3.03 mm [13]. In this study, distal implant position significantly influenced a greater horizontal deviation. All models studied had anterior teeth that were used for trace registration. Thus, this factor might contribute to higher horizontal accuracy for a mesial implant in a premolar-molar area. In addition, this could be supported by data showing a tendency for a higher horizontal deviation in K1 and K2 model groups (fewer teeth in the posterior region for trace registration) compared to the K3 group. Also, the mesial implant was of a smaller diameter (3.8 mm compared to 4.3 mm) and shorter (11 mm

compared to 13 mm) this takes less instrumentation for implant bed preparation and might also play a role. Brief et al. (2005) reported some of the lowest horizontal deviations 0.35–0.65 mm. Still, they studied only the accuracy of an implant bed preparation by a pilot drill without implant delivery in a model which was not fixed in a mannequin [37]. Implant placement could add more variability and higher deviations. The largest horizontal deviations were reported by Kang et al. (2014), reaching 2–3 mm (increasing for the posterior region) for fully edentulous mandibular models, thus suggesting higher deviations in fully edentulous cases [36].

Angle deviations in the present study varied from 1.04 ± 0.53 to 4.5 ± 1.18°. These results are within the range for model studies of all 3 systematic reviews on dynamic guidance accuracy published in 2021: 0.89–4.45 [14]; 0.82–5.49 [3]; 1.09–12.37 [13] degrees. K2 class showed significantly higher angle deviations than K1 and K3 classes, suggesting that unilateral defects, even with a higher number of teeth, might negatively affect the angular accuracy of the dynamic guidance. Furthermore, the distal implant position also showed a higher angle deviation compared to the mesial. Kang et al. (2014) reported contradicting findings - significantly higher angular deviation in the canine region (12.37 ± 4.18) compared to the molar (8.97 ± 3.83) [36]. The results might differ due to the involvement of the fully edentulous cases in the later study and the advancement in dental navigation systems over time. Significantly lower angular deviations for a mesial implant position were evident in both K2 class implant design subgroups. Distal implant position tended to show higher deviation in most subgroups except for K1 SL. This data is similar to horizontal deviations, both showing higher deviations for a distal implant position.

Wu et al. reported no significant differences between dynamic navigation and the static surgical guide in terms of coronal deviation, apical deviation, and angular deviation [38]. Other research on the accuracy of the navigation revealed that the mean coronal and apical deviations were less than 1.22 mm and 1.45 mm, respectively, and the angular deviation was less than 4.06° [39,40]. Chang-Kai et al. [41] reported similar mean horizontal deviation values at the apical endpoint when using a computer-aided dynamic navigation system (1.35 ± 0.55 mm), a computer-aided static navigation system (1.50 ± 0.79 mm), and manual implant placement (2 ± 0.79 mm). Higher angular deviation values were reported for the computer-aided dynamic navigation system (4.45 ± 1.97°), the computer-aided static navigation system (6.02 ± 3.71°), and manual implant placement (9.26 ± 3.62°).

The limitations of this study should be taken into account. Even though the latest systematic review papers show no difference between model and clinical studies [3,13,14], a model study does not simulate all the possible clinical factors such as soft tissue influence, patient head movement, possible detachment of head or jaw trackers, dental assistant, limited operating field accessibility and time. Also, other factors such as operators experience, IOS and CBCT quality might have influence towards the deviations. In addition, this model study was designed to simulate hard bone (D I). A hard bone situation requires a well-prepared implant bed. Still, on the other hand, a soft bone situation might lead to an easier drill or implant insertion deviation and sometimes requires much less instrumentation as well as changes in drill sequence (especially for bone type IV) [42]. Furthermore, the mesial implant position was also planned for a smaller diameter and shorter implant in this study, this difference in implant parameters could influence the deviation differences when comparing mesial and distal implant positions. In addition, distal implant position (molar area) received a wider and longer implant which may not clinically possible in some patients due to proximity of a maxillary sinus floor. On the other hand, scientific evidence shows that implant size is selected considering the anatomical situation and occlusal load in premolar and molar areas [43–45]. Finally, IOS accuracy evaluation method has limitations due to images stiching and other related aspects. There are more precise methods available for a model based accuracy evaluation. This study employed the tools and methods that are clinically relevant to a standard fully-guided implant treatment workflow.

5. Conclusions

This study is amongst the first evaluating fully-guided dynamic implantation accuracy with a X-ray-free post-operative method. Within the limitations of this study, the results show high accuracy for all deviations of the procedure concerning all the factors analysed: edentulous defect Kennedy class, implant design and implant position (mesial or distal). The following conclusions can be drawn:

- An overall (insertion point) deviation for a less conical implant design (SL) might be negatively influenced by distal implant position, whereas the position shows no influence for a more aggressive implant design (PL).
- A more aggressive implant design shows lower depth deviations for a single tooth defect.
- Depth deviations for a more aggressive implant design might be negatively influenced by distal implant position.
- A less aggressive implant design (SL) might have positive influence in reducing depth deviations in a premolar area.
- Angle deviations were influenced the most by all the factors (Kennedy class, implant design and position) and their interactions.

CRediT authorship contribution statement

Vygandas Rutkunas: Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing – review & editing, Supervision, Project administration. **Ieva Gendviliene:** Data curation, Formal analysis. **Liudas Auskalnis:** Resources, Project administration. **Francesco Mangano:** Supervision, Project administration. **Stefan Zlatev:** Investigation, Writing – original draft, Visualization. **Vasilena Ivanova:** Writing – review & editing, Project administration, Supervision. **Eitan Mijiritsky:** Data curation, Formal analysis, Writing – review & editing, Supervision. **Rokas Borusevicius:** Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Visualization.

Declaration of Competing Interest

The authors declare no conflict of interests. The Navident and Oral Reconstructive Foundation donated the materials for the study. The study was supported by the Lithuanian Business Support Agency grant Nr. J05-LVPA-K-01-0055 and DIGITORUM research team.

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