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An in-vitro analysis of the accuracy of different guided surgery systems – They are not all the same

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Abstract

Objectives: Different static computer-assisted implant surgery (sCAIS) systems are available that are based on different design concepts. The objective was to assess seven different systems in a controlled environment.

Materials and Methods: Each $n=20$ implants were placed in identical mandible replicas (total $n=140$). The systems utilized either drill-handles (group S and B), drill-body guidance (group Z and C), had the key attached to the drill (group D and V), or combined different design concepts (group N). The achieved final implant position was digitized utilizing cone-beam tomography and compared with the planned position. The angular deviation was defined as the primary outcome parameter. The means, standard deviation, and 95%-confidence intervals were analyzed statistically with 1-way ANOVA. A linear regression model was applied with the angle deviation as predictor and the sleeve height as response.

Results: The overall angular deviation was $1.94 \pm 1.51°$, the 3D-deviation at the crest 0.54 ± 0.28 mm, and at the implant tip 0.67 ± 0.40 mm, respectively. Significant differences were found between the tested sCAIS systems. The angular deviation ranged between $0.88 \pm 0.41°$ (S) and $3.97 \pm 2.01°$ (C) ($p < .01$). Sleeve heights ≤4 mm are correlated with higher angle deviations, sleeve heights ≥5 mm with lower deviations from the planned implant position.

Conclusions: Significant differences were found among the seven tested sCAIS systems. Systems that use drill-handles achieved the highest accuracy, followed by the systems that attach the key to the drill. The sleeve height appears to impact the accuracy.

KEYWORDS
accuracy, computer-assisted implant surgery, guided implant surgery, open sleeve, precision, surgical stent, trueness

1 | INTRODUCTION

Guided implant surgery, also referred to as computer-assisted implant surgery (CAIS), is more accurate than free-hand implant placement (Gargallo-Albiol et al., 2020; Tattan et al., 2020; Younes et al., 2018). The higher the degree of guidance (pilot guided versus fully guided), the higher is the accuracy of reproducing the digitally planned position into the delivered implant position (Lou et al., 2021; Putra et al., 2022; Younes et al., 2018). Guided implant surgery allows therefore for an accurate three-dimensional implant positioning based on the bone availability (Ramanauskaite et al., 2019) and ideal prosthetic implant position (Chackartchi et al., 2022) which increases the predictability of favorable emergence profile and soft tissue esthetics (Fürhauser et al., 2015).

The development in digital technology allows for three different main approaches in computer-assisted guided implant surgery based on a digitally planned implant position: (i) designing of a static surgical guide and using this template to guide the drills while performing the osteotomy and/or placing the implant through that guide (D'Haese et al., 2017), (ii) using navigated systems where cameras monitor the 3D position of the handpiece in relationship to the treated jaw while performing the osteotomy (Vercruyssen, Fortin, et al., 2014), or (iii) robotic systems where the drilling process is devolved to a machine (Mozer, 2020). While the latter two approaches might be technologically more advanced, they have yet to show clinical superiority over static surgical guides (Demetoglu et al., 2021). Low costs for planning and producing digital planned static surgical guides (Jorba-Garcia et al., 2021) makes this technology an attractive tool to improve the quality of implant surgery and patient experience, and to reduce the surgical risk (Joda et al., 2018).

Implant companies are using different approaches for static computer-assisted implant surgery (sCAIS) in the way the drills are guided while performing the osteotomy. All systems require a tube or also called sleeve cylinder of a defined diameter and height to house the drills. The drills themselves (a) can have vertical stops and use surgical keys or drill-handles that have an inner hole with a diameter that is specific to the diameter of the respective drill and have an outer dimension that matches the sleeve cylinder in the guide, (b) have a drill shank of the compatible diameter as the inner diameter of the sleeve cylinder, which allows for drill-body guidance, or (c) can have a surgical key attached that matches the inner diameter of the sleeve cylinder (key-on-drill). The latter two approaches are considered key-less and do not require a drill-handle.

The literature is inconsistent if the findings for one guided surgery concept apply to others as well (Guentsch et al., 2022; Laederach et al., 2017; Sittikornpaiboon et al., 2021; Yeung et al., 2020). The aim of this study is to compare the accuracy of seven different systems using (a) drill-handles, (b) drill-body guidance/shank-modified drills, or (c) key-on-drill concepts under standardized conditions with repeated measurements. The null hypothesis is that there is no difference in the accuracy of different static-computer assisted implant surgery systems.

2 | MATERIALS AND METHODS

2.1 | Experimental preparations

A cone beam computed tomography (CBCT) scan of a patient with bounded edentulous spaces was retrieved and a standard tessellation language (STL) file of the mandible was generated. The STL file was used for stereolithographical printing (Grey resin version 4 using the Form 3B printer; all Formlabs Inc) to replicate 140 identical mandibles. The CBCT was obtained solely for medical reasons and the local IRB committee (Office of Research Compliance, Marquette University, Milwaukee, WI) approved the protocol (HR-1807025341) to use the CBCT for research purposes. Research standards as described in the Declaration of Helsinki have been followed. The selection criteria for the mandible included (a) the presence of sufficient number of teeth for adequate guide support, (b) good distribution of teeth for triangulation of clinical markers, (c) minimal number of dental restorations which could lead to artefacts in the CBCT, and (d) vertical and horizontal bone height that allowed for ideal implant positioning.

A single implant for the position of the first lower right molar was virtually planned with an implant planning software program (coDiagnostiX; Dental Wings GmbH). The 3D position of the implant was not altered throughout the planning and analysis process, but the type of the fixture was changed to accommodate the respective guided surgery systems and their matching sleeves and instruments. Table 1 reports the used guided surgery systems, and the implant fixture dimensions that were used for the respective systems. Sleeves in dimensions recommended by the manufacturer were used and the sleeve-to-bone distance (offset between bottom of sleeve and top of implant platform at crest level) was set at 2 mm for all systems. Surgical guides were designed in a standardized manner whereas the guide extended over 3/4 of the mandible (lower left canine to lower right second molar) for the planned implants. The guides were 3D-printed with a Class I biocompatible resin (Surgical Guide resin, Formlabs Inc) and the experiments performed within 1 week after the guides were produced.

2.2 | Treatment groups

The bench-test was performed under standardized conditions. The sequential drilling of all osteotomies was performed according to manufacturer recommendations. The implants ($n = 20$ per system) were placed through the guide, except for the V-group (universal system). All surgical procedures were performed by the same operator for consistency. In total $n = 7$ guided surgery systems were compared in this study (please see Table 1 for details), each $n = 2$ systems that (a) use drill-handles (DH) to guide the drills, (b) use the drill-body for guidance (DBG), or (c) have the key attached to the drill (KOD). Additionally, (d) one system that combines drill-handle and drill-body guidance was investigated as a hybrid-system (HS). Figure 1 illustrates the different guided surgery systems using drill-handles (Figure 1a,b), shank-modified drills (Figure 1c,d), or having

TABLE 1 Characteristics of the guided surgery systems used for comparison.

Guided surgery groups	Guided surgery systems		Implant dimension[a]		Sleeve cylinder			
	Label	Product information	Diameter (in mm)	Length (in mm)	Diameter (in mm)	Height (in mm)	Drill guidance[b] (in mm)	Sleeve offset[c] (in mm)
Key-on-drill (KOD)	D	Astra Tech Implant System EV (Dentsply-Sirona, Charlotte, NC, USA)	4.20	11.00	5.60	4.00	5.00	2.00
	V	Versah Universal Guided Surgery System, Gen2 (Versah, Jackson, MI, USA)	4.10	10.00	6.20	6.25	6.25	2.00
Drill-handle (DH)	S	Straumann Guided Surgery (Institut Straumann, Basel, Switzerland)	4.10	10.00	5.00	5.00	8.00	2.00
	B	BioHorizons Guided Surgery Kit, (BioHorizons, Birmingham, AL, USA)	4.00	10.50	4.60	6.00	8.00	2.00
Drill-body guided (DBG)	Z	RealGuide Z3D (ZimVie, Palm Beach Gardens, FL, USA)	4.10	10.00	5.05	3.50	3.50	2.00
	C	Camlog Guide System PL (Camlog, Basel, Switzerland)	4.30	11.00	4.30	3.00	3.00	2.00
Hybrid system (HS)	N	NobelGuide (Nobel Biocare, Zurich, Switzerland)	4.30	10.00	5.00	3.50	3.50	2.00

[a]Results are presented for a standardized length of 10 mm for all implants and systems.
[b]Distance that the drill is guided in the sleeve cylinder +/− key height (if applicable).
[c]Sleeve-bone-distance, bottom of sleeve to top of implant platform.

the key attached to the drill (Figure 1e,f). The hybrid system uses a drill-handle seated into the sleeve cylinder to guide the initial drills (Figure 1g) while other drills are drill-body guided (Figure 1h).

2.3 | Data acquisition

Post-operative CBCTs were obtained from all mandibles (using the following parameters: XS patient size, teeth field of visualization, 90 kV, 71 mAs, 150 μm, and artifact reduction algorithm; Viso G-7, Planmeca, Helsinki, Finland). The CBCT files were loaded into the implant planning software. The actual implant position from the post-operative CBCT was compared with the virtually planned (reference) with the treatment evaluation tool of the planning software for each implant. According to the International Organization for Standardization (ISO) standard 5725, accuracy is defined by the trueness (here: planned vs. actual position) and the precision (here: difference among implants) of a method. The angular deviation from the reference position was defined as primary outcome parameter. The 3D deviations at the crest and apex of the implant as well as 2D deviations in mesial-distal, vestibular-oral, and coronal-apical direction at the crest and apex were evaluated (see Figure 2). The treatment evaluation was performed single-blinded.

2.4 | Statistical analysis

An a-priori sample size calculation based on previous data suggested $n = 20$ samples per group (in total $n = 140$) with a p value of <.05 and with an effect size of 0.40 for a targeted 80% power (Guentsch et al., 2021). A post-hoc power analysis was performed by calculating the power based on the angle deviation between the two groups with the greatest difference (Camlog vs Straumann), given the collected sample size, mean difference, and the maximum standard deviation of these two systems (statistical software R version 4.2.2). The calculated power of this study was 99%. This further justifies the required sample size prior to collecting the sample with desired power.

Means, standard deviations, and 95%-confidence intervals were calculated for primary and secondary outcome parameters (IBM SPSS Statistics 28.0). A one-way analysis of variance (ANOVA) was performed to analyze the overall statistically significant difference among all groups. Scheffe's multiple comparisons were utilized to assess the differences between the groups.

A linear regression analysis including coefficient parameter estimate, confidence interval, and p values was performed (R version 4.2.2) to assess correlations between sleeve height and angle deviations.

3 | RESULTS

The overall angular deviation for all $n = 140$ implants was $1.94 \pm 1.51°$, and the 3D-deviation at the crest 0.54 ± 0.28 mm and at the implant tip 0.67 ± 0.40 mm, respectively.

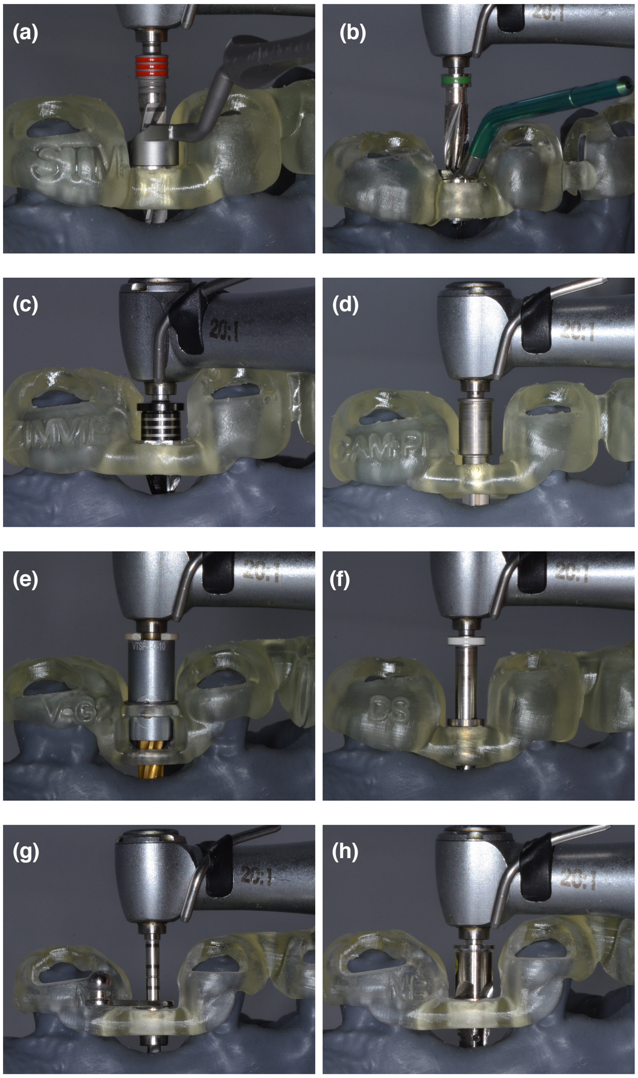

FIGURE 1 Representative images of the different sCAIS systems. The top row shows the two drill-handle guided systems (a: Straumann, b: BioHorizons), where the drill-handle is placed into the sleeve cylinder and the drill guided through a corresponding drill channel within the key. The second row from the top illustrates the two shank-modified, drill-body guided systems (c: ZimVie, d: Camlog), both are keyless systems where the drill shank has a corresponding diameter to the sleeve cylinder. The third row depicts the two key-on-drill systems (e: Versah, f: Astra Tech/Dentsply Sirona). Here the key is attached to the drill. In e, incrementing key heights are used until the final depth is reached, while in f the key height is constant for all drills, but the drills have specific lengths with a vertical stopper. The bottom row shows one sCAIS system (NobelBiocare) that combines different concepts. The initial drills are using a surgical key (g), while the guided taper drills are directly guided through the shank (h).

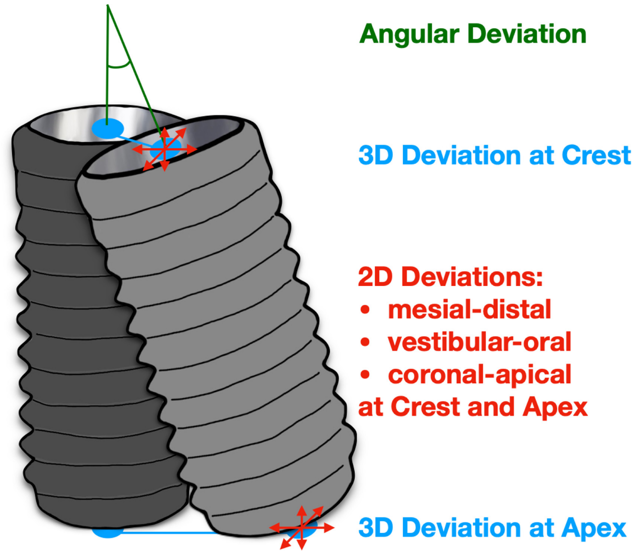

FIGURE 2 Deviations measured from the planned position (dark grey implant) to the actual delivered implant position (light grey).

Statistically significant differences for all investigated parameters were detected between the different guided surgery systems, with large between-group variations for the angular deviation (F-value 14.99), the 3D-deviation at the crest (F-value 19.09), the tip (F-value 13.02), and the apical deviation (F-value 25.40).

The mean angular deviations of the investigated seven sCAIS systems ranged from 0.88° to 3.97° (Figure 3). Implants placed with the two drill-handle systems (S: 0.88 ± 0.41° and B: 1.22 ± 0.61°) and the key-on-drill systems (D: 1.91 ± 1.46° and V: 1.14 ± 0.39°) had lower angular deviations than the hybrid system (N: 2.37 ± 1.15°) and the drill-body guidance systems (Z: 2.00 ± 1.28° and C: 3.97 ± 2.01°). The angular deviations were significantly different between C in comparison to all other systems ($p < .01$), and additionally between S and N ($p < .01$).

The 3D-deviation at the crest ranged from 0.32–0.55 mm and at the apex from 0.35 to 1.07 mm, respectively. The results in terms of trueness are presented for all systems in Table 2 (means, standard deviation, and 95% confidence intervals). The findings show that there are significant differences between the groups. In mesial-distal direction, the 2D deviation ranges from 0.15 to 0.47 mm at the crest level ($p < .01$) and from 0.20 to 0.53 mm at the apex ($p < .01$). The vestibular-oral 2D deviations range at the crest level from 0.21 to 0.60 mm ($p < .01$) and at the tip of the implant from 0.22 to 0.61 mm ($p < .01$). The coronal-apical direction showed the greatest difference among the systems ($p < .01$), while the lowest value was 0.05 mm for both, crest and apex level, the highest deviation was measured with 0.60 mm (crest level) and 0.63 mm (apex level), respectively. The 2D-deviations in mesial-distal and vestibular-oral directions are illustrated in Figure 4. Each implant position is depicted as one data point. The closer the data points are to the center of the bull's eye (reference position set as zero), the higher is the trueness of the method. The distance among the data points represents the precision of the respective system. The closer the data points are to each other, the higher is the precision (Table 3).

Table 1 shows that the different guided surgery systems use sleeve cylinders with different heights. A linear regression model with

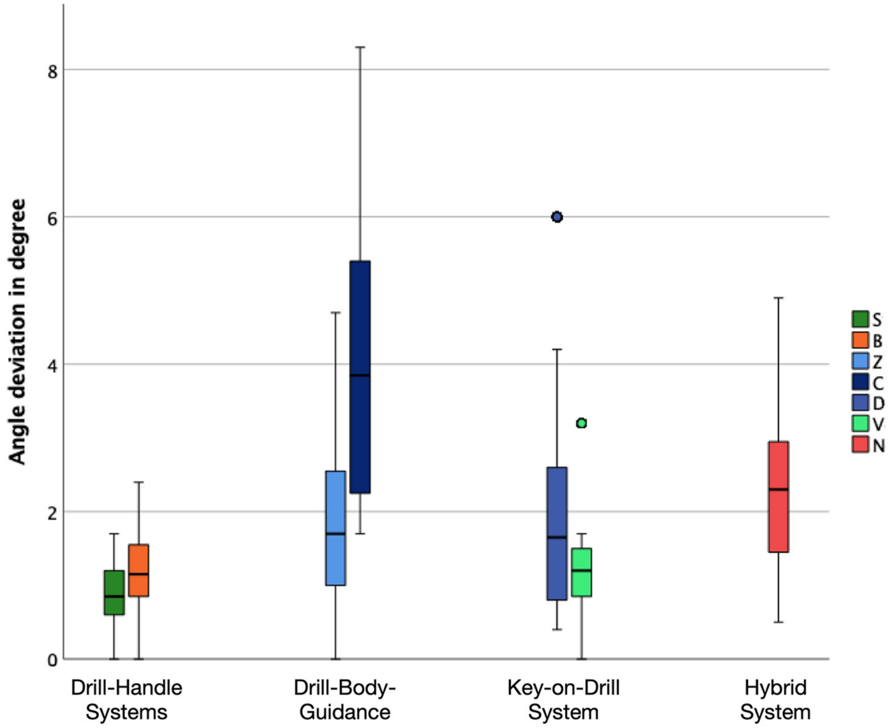

FIGURE 3 Angle deviations in degree presented as boxplots for all $n = 7$ different sCAIS systems. (n.s. – no significant difference, S – Straumann, B – BioHorizons, Z – ZimVie, C – Camlog, D – Dentsply Sirona. V – Versah, N – NobelBiocare)

the angle deviation as response and the sleeve height as predictor was used to calculate coefficient estimates. The 140 data points were split in two groups of ≤4 mm and ≥5 mm sleeve height. When the cutoff is ≤4 mm sleeve height, a 1 mm increase in sleeve height would result in 2.06° decrease in angular deviation; however, a 1 mm increase of sleeve height for the group with sleeve heights ≥5 mm would lead to 0.3° increase of angulation. Figure 5 illustrates the regression lines.

4 | DISCUSSION

This in-vitro study assessed the accuracy of seven different guided surgery systems that are widely used for static computer-assisted implant surgery. There were significant differences in angular deviation, 3D as well as 2D deviations between the different groups. Therefore, the null hypothesis that all guided surgery systems provide the same accuracy was rejected. In fact, systems differ by the factor of 4.5 when it comes how much the actual implant angle deviates from the planned implant position. The highest discrepancy among systems was found in terms of coronal-apical deviation (factor of 12.6). Additionally, the present study revealed that the sleeve height impacts the angular deviation. Short sleeve cylinders are correlated with higher angular deviation, while sleeve cylinder heights of 5 mm and more corresponded with lower angles.

It was repeatedly reported that static computer assisted implant surgery (sCAIS) is more accurate than implant surgery without the use of a surgical guide (Smitkarn et al., 2019; Vercruyssen, Hultin, et al., 2014; Younes et al., 2018). When reviewing the findings of meta-analyses from the last 5 years (Table 4), the reported angular deviation for sCAIS is within a range of 2.20–5.95°, the 3D deviation at the crest is within a range of 0.55–2.34 mm and at the apex of 0.76–2.53 mm (Bover-Ramos et al., 2018; Gargallo-Albiol et al., 2020; Putra et al., 2022; Raico Gallardo et al., 2017; Tahmaseb et al., 2018; Tattan et al., 2020; Zhou et al., 2018). However, these systematic reviews and meta-analyses did not differentiate among guided surgery systems.

Studies comparing different guided surgery systems are rather rare, but the few studies that included more than one system suggest that there are differences and all guided surgery systems are not the same. This is critical to understand for clinicians as findings from one system cannot be necessarily generalized and translated to another system, especially when the systems follow different concepts of drill guidance.

A recent study from the University of Bangkok compared different sCAIS systems based on drill-handle guidance (Straumann), key-on-drill guidance (Dentsply-Sirona), and drill-body guidance (Dentium). The authors found significant differences in terms of angular deviation between the drill-handle system and the drill-body guidance system, which is confirming the observation made in the present study. Lower 3D-deviatons at the crest and the apex were also measured for Straumann, in comparison to the Densply-Sirona's Astra Tech Implant System (Sittikornpaiboon et al., 2021). A recent study showed that Straumann and Versah resulted in comparable angular deviations when the sleeve offset was 2 mm, and both sCAIS systems were significantly more accurate than when a surgical guide was only used for the pilot drill, or the osteotomy was performed without a surgical guide free-handed (Guentsch et al., 2022).

However, it cannot be concluded that all systems using a specific concept (e.g., drill-handle, or drill-body guidance) perform similarly good or bad. Yeung et al. (2020) found that three different systems showed differences in terms of angular, and 2D plane deviations. The guided systems from Zimmer and BioHorizons had

TABLE 2 Trueness of implant position as discrepancy between planned and actual position. Means, standard deviation (SD), and 95% confidence intervals [95%-CI] of discrepancies between reference and actual position for $n = 20$ implants per group.

Trueness (planned versus placed)		Drill-handle-systems		Drill-body-systems		Key-on-drill-systems		Hybrid system	ANOVA	
		S	B	Z	C	D	V	N		
		Mean (SD) [95%-CI]	Mean(SD) [95%-CI]	Mean (SD) [95%-CI]	Mean (SD) [95%-CI]	Mean (SD) [95%-CI]	Mean (SD) [95%-CI]	Mean (SD) [95%-CI]	*F*-value	*p*-Value
Angle in degree		0.88^{CN} (0.41) [0.69–1.0]	1.22^{C} (0.61) [0.93–1.50]	2.00^{C} (1.28) [1.40–2.61]	3.97* (2.01) [3.03 – 4.91]	1.91^{C} (1.46) [1.23–2.59]	1.14^{C} (0.39) [0.96–1.32]	2.37^{CS} (1.15) [1.83–2.90]	14.99	<.001
Crest	Δ3D	0.32^{CD} (0.14) [0.26–0.39]	0.53^{C} (0.16) [0.46–0.61]	0.40^{C} (0.14) [0.33–0.46]	0.93* (0.31) [0.79 – 1.07]	0.62^{CSV} (0.26) [0.50–0.75]	0.38^{CD} (0.14) [0.26–0.39]	0.55^{CS} (0.26) [0.43–0.68]	19.09	<.001
	Distal	0.19^{N} (0.11) [0.14–0.24]	0.18^{N} (0.16) [0.11–0.25]	0.15^{N} (0.12) [0.09–0.20]	0.15^{N} (0.12) [0.09–0.21]	0.31 (0.18) [0.22–0.39]	0.18^{N} (0.14) [0.11–0.24]	0.47^{BCSVZ} (0.24) [0.35–0.58]	11.09	<.001
in mm	Buccal	0.21^{C} (0.16) [0.14–0.28]	0.42 (0.21) [0.33–0.53]	0.21^{C} (0.16) [0.13–0.29]	0.60^{DNSZV} (0.24) [0.48–0.71]	0.30^{C} (0.22) [0.19–0.40]	0.27^{C} (0.12) [0.22–0.32]	0.21^{C} (0.22) [0.11–0.32]	10.90	<.001
	Apical	0.05^{CD} (0.05) [0.03–0.08]	0.20^{C} (0.14) [0.14–0.26]	0.24^{C} (0.14) [0.17–0.30]	0.60^{BNSVZ} (0.33) [0.44–0.75]	0.36^{SV} (0.26) [0.24–0.48]	0.08^{CD} (0.16) [0.01–0.15]	0.17^{C} (0.27) [0.04–0.29]	15.35	<.001
Apex	Δ3D	0.35^{CDN} (0.16) [0.28–0.42]	0.64^{C} (0.25) [0.53–0.76]	0.59^{C} (0.27) [0.46–0.72]	1.07^{BSVZ} (0.41) [0.88–1.27]	0.84^{SV} (0.39) [0.66–1.02]	0.37^{CDN} (0.26) [0.25–0.49]	0.85^{SV} (0.45) [0.64–1.06]	13.02	<.001
	Distal	0.24^{N} (0.11) [0.19–0.29]	0.25^{N} (0.16) [0.17–0.32]	0.24^{N} (0.14) [0.18–0.31]	0.35 (0.26) [0.23–0.47]	0.42 (0.27) [0.30–0.58]	0.20^{N} (0.16) [0.13–0.27]	0.53^{BSVZ} (0.42) [0.33–0.72]	5.13	<.001
in mm	Buccal	0.22^{C} (0.18) [0.14–0.30]	0.49 (0.31) [0.35–0.63]	0.42 (0.29) [0.29–0.56]	0.61* (0.44) [0.40–0.82]	0.52 (0.38) [0.34–0.69]	0.28 (0.25) [0.16–0.40]	0.54 (0.38) [0.36–0.71]	3.70	.002
	Apical	0.05^{CD} (0.05) [0.03–0.08]	0.20^{C} (0.14) [0.14–0.27]	0.24^{C} (0.14) [0.18–0.31]	0.63* (0.33) [0.47 – 0.78]	0.37^{CNSV} (0.27) [0.24–0.49]	0.05^{CD} (0.06) [0.02–0.08]	0.12^{CD} (0.08) [0.08–0.15]	25.40	<.001

Note: Capital letters refers to significant difference of $p < .05$ to respective guided implant system (S-Straumann, B-BioHorizons, Z-ZimVie, C-Camlog, D-Dentsply Sirona, V-Versah, N-Nobel Biocare).
*$P < .05$ significant different to all other systems.

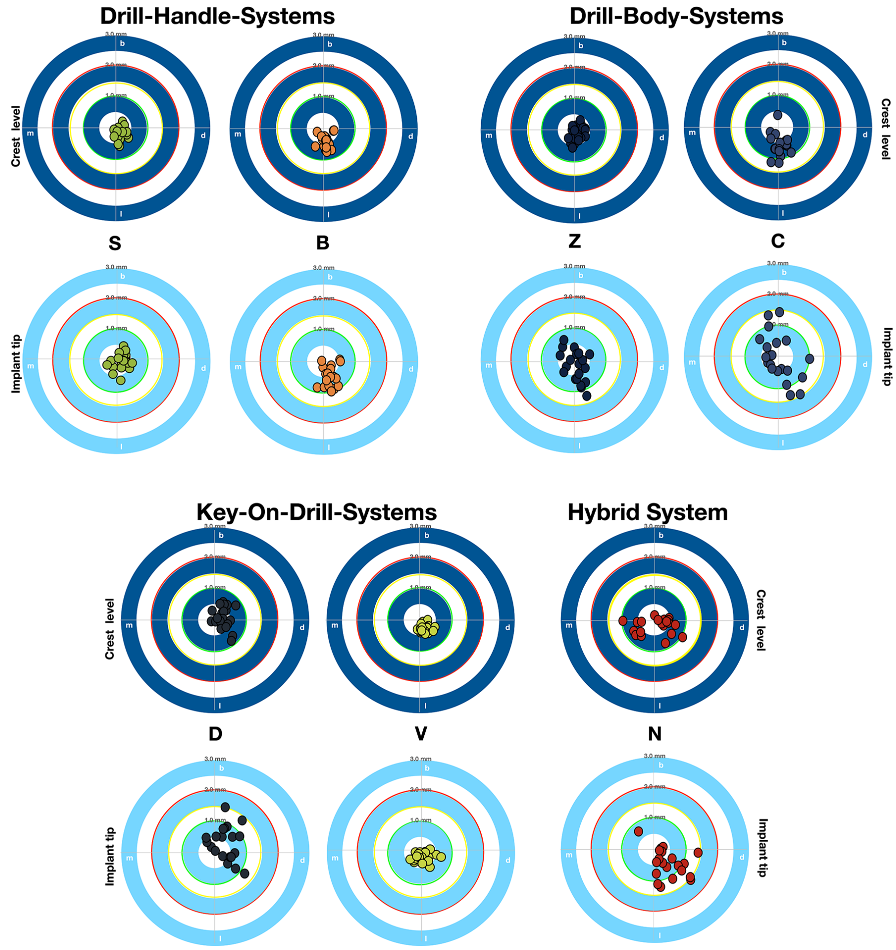

FIGURE 4 Mesial-distal and vestibular-oral deviation (in mm) as bull's-eye diagrams. The top row shows the 2D deviation at the crest level and the bottom row at the implant tip. All systems stay within the proposed 2 mm safety margin. Differences in trueness (closeness to center) and precision (distance among data points) become apparent.

lower angular deviations than the NobelGuide, but the system from NobelBiocare had the least deviation among the three systems in vertical dimension (Yeung et al., 2020). While angular and 3D deviation at the apex can become critical when there is proximity to vital anatomical structures (Tatakis et al., 2019), accuracy of guided systems in the coronal-apical direction is critical for complex prosthetic restorations where a predetermined interocclusal space must be delivered (Abduo & Lau, 2021). The lowest coronal-apical deviation in this study was found for the Straumann guided system (0.05 ± 0.05 mm), and the highest discrepancy was seen for the Camlog guide (0.60 ± 0.33 mm; $p < .01$).

When implantologists are using drill-handle systems, the implant drill is guided through the drill keys that is inserted into the sleeve cylinder, whereas in key-on-drill systems and drill-body guidance systems the drill is directly stabilized through the surgical guide. Holding a drill key might be considered an ergonomic disadvantage over key-less systems, as the operator needs to hold the key manually, but drill-handle systems delivered higher accuracy outcomes compared to shank-modified drills (Sittikornpaiboon et al., 2021).

Laederach et al. (2017) compared four different guided implant surgery systems in terms of deviations when centric or eccentric forces are applied. The authors found significant differences between the tested systems, especially in terms of angular deviation. The highest angular deviation was found for the Camlog guided system (3.21 ± 1.32°) and the lowest for the Straumann guided surgery system (0.04 ± 0.03°). This mirrors the findings of the present study where significant differences between these two systems were also found. Laederach and colleagues also observed that the increase of angular deviation was higher for Camlog's and NobelBiocare's guided system in comparison to the guided surgery system from Straumann when eccentric forces were applied (Laederach et al., 2017). Possible explanations can be a higher degree of tolerance within the sleeve cylinder and the drill-body (Van Assche & Quirynen, 2010), or the shorter drill guidance (El Kholy et al., 2019). These factors were shown to have an impact on the accuracy of guided implant surgery. The tested system in the present experiment with the highest sleeve cylinder height and longest drill guidance (Straumann, Versah, BioHorizons) had the lowest angular deviation. A regression analysis revealed that short sleeve cylinder heights of 4 mm or less correlate with high angular deviations, while sleeve cylinder heights of 5 mm or more are correlated with lower angular deviations. Other researchers also concluded that the sleeve cylinder length is a factor that is affecting angular deviations (Choi et al., 2004) and longer sleeve cylinders are critical for optimizing accuracy (Koop et al., 2013). If the tolerance between the drill and the sleeve cylinder is too high, the drill can be dislocated and cause unwanted lateral osteotomies. Shank-modifications as in

TABLE 3 Precision of implant placement as discrepancy among the implants. Means, standard deviation (SD), and 95% confidence intervals [95%-CI] of discrepancies among the actual implants for $n = 191$ comparisons per group.

Precision (as deviation among implants)		Drill-handle-systems: S Mean (SD) [95%-CI]	Drill-handle-systems: B Mean (SD) [95%-CI]	Drill-body-systems: Z Mean (SD) [95%-CI]	Drill-body-systems: C Mean (SD) [95%-CI]	Key-on-drill-systems: D Mean (SD) [95%-CI]	Key-on-drill-systems: V Mean (SD) [95%-CI]	Hybrid system: N Mean (SD) [95%-CI]	ANOVA: F-value	ANOVA: p-Value
Angle in degree		0.47^{CDNZ} (0.37) [0.42–0.52]	0.70^{CDNZ} (0.54) [0.62–0.78]	1.50^{BCSV} (1.08) [1.35–1.66]	2.32* (1.77) [2.07 – 2.58]	1.58^{BCSV} (1.33) [1.40–1.77]	0.44^{CDNZ} (0.39) [0.38–0.49]	1.34^{BCSV} (0.99) [1.20–1.48]	84.20	<.001
Crest	Δ3D	0.16^{CDN} (0.12) [0.14–0.18]	0.20^{CDN} (0.14) [0.18–0.22]	0.16^{CDN} (0.12) [0.14–0.18]	0.36^{BSVZ} (0.25) [0.32–0.39]	0.31^{BSVZ} (0.22) [0.28–0.34]	0.15^{CDN} (0.13) [0.14–0.17]	0.30^{BSVZ} (0.22) [0.27–0.33]	43.70	<.001
	Distal	0.15 ND (0.10) [0.14–0.17]	0.16^{N} (0.13) [0.14–0.18]	0.19^{N} (0.13) [0.17–0.21]	0.21^{N} (0.16) [0.20–0.24]	0.24^{NS} (0.17) [0.21–0.26]	0.16^{N} (0.12) [0.15–0.18]	0.61* (0.44) [0.55 – 0.67]	114.34	<.001
in-mm	Buccal	0.22^{CDV} (0.16) [0.20–0.24]	0.25^{CDV} (0.17) [0.23–0.28]	0.28^{CDV} (0.19) [0.25–0.31]	0.39^{BNSVZ} (0.31) [0.34–0.43]	0.42^{BNSVZ} (0.30) [0.38–0.46]	0.13* (0.10) [0.12 – 0.15]	0.28^{CDV} (0.21) [0.25–0.31]	37.44	<.001
	Apical	0.08^{BCDNZ} (0.07) [0.07–0.09]	0.16^{CDN} (0.11) [0.14–0.18]	0.19^{CDSV} (0.15) [0.17–0.21]	0.39* (0.27) [0.35 – 0.42]	0.31^{BCSVZ} (0.22) [0.27–0.34]	0.08^{BCDZ} (0.07) [0.08–0.10]	0.25^{BCSV} (0.34) [0.21–0.30]	60.62	<.001
Apex	Δ3D	0.18^{BCDNZ} (0.15) [0.16–0.20]	0.32^{CDNS} (0.24) [0.28–0.35]	0.31^{CDNS} (0.24) [0.28–0.35]	0.49^{BNSVZ} (0.37) [0.43–0.54]	0.49^{BNSV} (0.36) [0.44–0.54]	0.26^{CDN} (0.27) [0.23–0.30]	0.62* (0.42) [0.56 – 0.68]	47.98	<.001
	Distal	0.24^{CDN} (0.18) [0.21–0.26]	0.25^{CDN} (0.17) [0.23–0.28]	0.33^{CDN} (0.23) [0.29–0.36]	0.56^{BSVZ} (0.43) [0.50–0.62]	0.45^{BNSVZ} (0.31) [0.41–0.50]	0.29^{CDN} (0.21) [0.26–0.32]	0.62^{BDSVZ} (0.47) [0.55–0.69]	48.34	<.001
in mm	Buccal	0.31^{CDNZ} (0.23) [0.28–0.34]	0.41 (0.28) [0.37–0.45]	0.59^{BCSV} (0.40) [0.53–0.65]	0.98* (0.68) [0.89 – 1.10]	0.71^{BCSV} (0.50) [0.64–0.78]	0.30^{CDNZ} (0.38) [0.24–0.35]	0.64^{BCSV} (0.46) [0.58–0.71]	59.72	<.001
	Apical	0.08^{BCDZ} (0.07) [0.07–0.09]	0.16^{CDSV} (0.11) [0.15–0.18]	0.20^{CDNSV} (0.15) [0.18–0.22]	0.38* (0.27) [0.34 – 0.42]	0.31* (0.23) [0.28 – 0.34]	0.08^{BCDZ} (0.08) [0.07–0.09]	0.11^{CDZ} (0.08) [0.10–0.12]	101.67	<.001

Note: Capital letters refer to significant difference of $p < .05$ to respective guided implant system (S-Straumann, B-BioHorizons, Z-ZimVie, C-Camlog, D-Dentsply Sirona, V-Versah, N-Nobel Biocare).
*$P < .05$ significant different to all other systems.

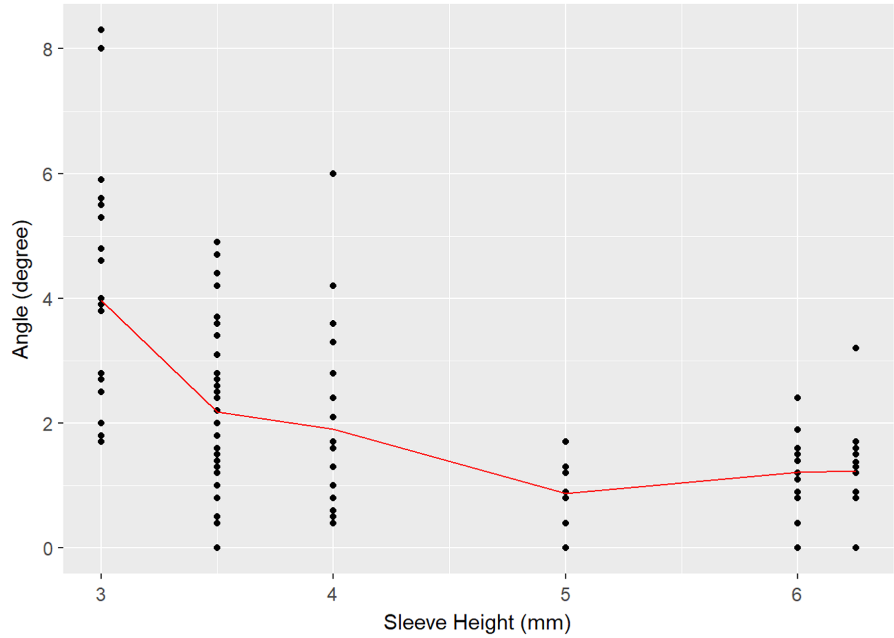

FIGURE 5 Regression line for angle deviation and sleeve cylinder height. The shorter the sleeve height, the higher the angle deviation. The regression line flattens from sleeve heights 5 mm and more.

TABLE 4 Reported accuracy (here in terms of trueness) of static computer-assisted implant surgery reported in meta-analyses of clinical trials. There is a wide range of accuracy reported in the literature, which can differ among trials and meta-analyses by the factor of 2.5 and more.

Meta-analysis/systematic reviews	Study characteristics	Mean angular deviation (in degree) Mean [95% CI] or (SD)	Deviation at crest (in mm) Mean [95% CI] or (SD)	Deviation at apex (in mm) Mean [95% CI] or (SD)
Raico Gallardo et al. (2017)	Tooth Supported	3.5 (1.38)–4.40 (1.60)	0.81 (0.33)–1.31 (0.59)	1.01 (0.40)–1.62 (0.54)
	Bone supported	4.73 (1.28)–5.10 (2.70)	1.30 (1.00)–1.70 (0.52)	1.60 (1.50)–1.99 (0.64)
	Mucosa supported	2.90 (0.39)–4.90 (2.20)	0.70 (0.13)–1.24 (0.51)	0.76 (0.15)–1.70 (1.00)
Bover-Ramos et al. (2018)	RCTs	3.62 (0.29)	1.08 (0.10)	1.35 (0.12)
Tahmaseb et al. (2018)	Partially edentulous	3.3 [2.07–4.63]	0.9 [0.79–1.00]	1.2 [1.11–1.20]
	Fully edentulous	3.3 [2.71–3.88]	1.3 [1.09–1.56]	1.5 [1.29–1.62]
Zhou et al. (2018)	RCTs	3.14 (0.7)	0.75 (0.25)	0.88 (0.32)
Tattan et al. (2020)	RCTs	2.20 (1.10)–5.95 (0.87)	0.54 (0.33)–2.34 (1.01)	0.90 (0.43)–2.53 (1.11)
Gargallo-Albiol et al. (2020)	RCTs	2.30 (0.92)–3.68 (2.40)	0.55 (0.11)–1.00 (0.60)	0.81 (0.21)–1.11 (0.71)
Putra et al. (2022)	RCTs	2.30 (4.22)–3.04 (1.51)	0.73 (0.46)–1.40 (0.54)	0.97 (0.87)–1.59 (0.59)
Range of Reported Accuracy for sCAIS		2.20 (1.10)–5.95 (0.87)	0.55 (0.11)–2.34 (1.01)	0.76 (0.15)–2.53 (1.11)

Abbreviations: CI, confidence interval; RCTs, randomize clinical trials; sCAIs, static computer-assisted implant surgery (only data for fully guided surgery presented); SD, standard deviation.

the drill-body guided systems are intended to reduce lateral drilling motions and therefore improve the accuracy of guided implant placement (Chackartchi et al., 2022). However, the results of the present study show the shank-modified drilling systems were not superior to drill-handle systems or a system with the key attached to the drill. A significant difference was observed in terms of accuracy between the two tested drill-body guided systems. Increasing the sleeve cylinder heights or the overall length of drill guidance may improve the accuracy of the tested systems.

The limitations of this study need to be considered when interpreting the findings. The in-vitro study design simulates a complex surgical procedure. The deviations from the planned implant positions are the cumulation of technical errors during examination, implant planning, surgical guide production, and surgical procedure (Putra et al., 2022). Implant placement accuracy was found to be lower in clinical studies compared to bench top tests. Therefore, the results in this study are ideal outcomes, knowing that the angular deviation can be significantly higher (by the factor of 1.7) under real life conditions, due to clinical factors such as limited mouth opening, saliva, bleeding, mucosal resilience, and different bone densities (Bover-Ramos et al., 2018). The latter was not replicated in the mandible samples. The resin used for the fabrication of the specimens produced a homogenous material, which does not represent natural bony conditions with cortical and cancellous bone segments.

However, a high degree of standardization in the experimental set-up with elimination of the previously mentioned co-founding factors as in this study design allows for the direct comparison of the changing variable in the experiment, which is the guided surgery system. Further, while clinical trials can only measure the trueness in terms of closeness to the reference (here planned implant position), in-vitro tests with repeated measurements in identical specimen allow one to assess the precision of the technique which refers to the closeness of agreements between test results (ISO-5725-1:1994(E), 2018). The standardization of this study included the use of the same implant planning software, the same method of guide and specimen production for all tested guided surgery systems, a single operator performing all procedures, and standardized data collection and analysis. The sleeve-bone-distance (offset) was 2 mm for all systems. Previous research showed that the sleeve distance to the implant platform has a significant effect on the accuracy of sCAIS (El Kholy et al., 2019). The closer the sleeve is to the bone, the higher is the accuracy (Guentsch et al., 2021). Future research should investigate if this is true for all guided surgery concepts.

Accurate three-dimensionally positioned implants enable the final restoration to be optimally designed (Chackartchi et al., 2022) and reduce the risk of future soft- and hard tissue loss (Hämmerle & Tarnow, 2018). While fully guided implant surgery is more accurate than free-hand or pilot-guided implant placement (Guentsch et al., 2022), different systems for sCAIS with diverse designs and protocols impact the accuracy of implant placement in terms of angular, 3D and 2D-deviation.

5 | CONCLUSIONS

Within the limitations of this study, significant differences among the seven tested sCAIS systems in terms of trueness and precision were observed. The concept of the guided surgery system can significantly affect the accuracy of implant placement. Drill-handle systems achieved less angular deviation than systems utilizing in full or partial drill-body guidance. The three systems with the highest trueness (planned vs actual position) and precision (variation in actual implant position) were found to be S, V, and B. Sleeve cylinders with 4 mm or less sleeve height correlated with higher angular deviation. Increasing the sleeve height beyond 5 mm, did not further reduce the angular deviation. Clinicians should be familiar with the strengths and weaknesses of the used sCAIS system and be trained to accommodate for system-related deviations.

AUTHOR CONTRIBUTIONS

A.G. conceived the ideas and performed the experiments. J.B. and R.S. collected the data and A.G. and S.H. analyzed the data. A.G. led the writing, A.R.D., S.H., R.S., and J.B. contributed to the writing.

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CONFLICT OF INTEREST STATEMENT

The authors declare in general no conflict of interest. AG received honorarium for speaking engagements from Versah.

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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REFERENCES

Abduo, J., & Lau, D. (2021). Seating accuracy of implant immediate provisional prostheses fabricated by digital workflow prior to implant placement by fully guided static computer-assisted implant surgery: An in vitro study. *Clinical Oral Implants Research*, *32*(5), 608–618. https://doi.org/10.1111/clr.13731

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*(1), 101–115. https://doi.org/10.11607/jomi.5556

Chackartchi, T., Romanos, G. E., Parkanyi, L., Schwarz, F., & Sculean, A. (2022). Reducing errors in guided implant surgery to optimize treatment outcomes. *Periodontology 2000*, *88*(1), 64–72. https://doi.org/10.1111/prd.12411

Choi, M., Romberg, E., & Driscoll, C. F. (2004). Effects of varied dimensions of surgical guides on implant angulations. *The Journal of Prosthetic Dentistry*, *92*(5), 463–469. https://doi.org/10.1016/S002239130400527X

Demetoglu, U., Bilge, S., Aslan, S., & Simsek, H. O. (2021). Comparison of the accuracy of pilot-drill-guided and fully guided implant surgery with dynamic navigation. In vitro model study. *The Journal of Oral Implantology*. Advance online publication. https://doi.org/10.1563/aaid-joi-D-20-00383

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*(1), 121–133. https://doi.org/10.1111/prd.12175

El Kholy, K., Janner, S. F. M., Schimmel, M., & Buser, D. (2019). The influence of guided sleeve height, drilling distance, and drilling key length on the accuracy of static computer-assisted implant surgery. *Clinical Implant Dentistry and Related Research*, *21*(1), 101–107. https://doi.org/10.1111/cid.12705

Fürhauser, R., Mailath-Pokorny, G., Haas, R., Busenlechner, D., Watzek, G., & Pommer, B. (2015). Esthetics of flapless single-tooth implants in the anterior maxilla using guided surgery: Association of three-dimensional accuracy and pink esthetic score. *Clinical Implant Dentistry and Related Research*, *17*(Suppl 2), e427–e433. https://doi.org/10.1111/cid.12264

Gargallo-Albiol, J., Barootchi, S., Marques-Guasch, J., & Wang, H. L. (2020). Fully guided versus half-guided and freehand implant placement: Systematic review and meta-analysis. *The International*

Journal of Oral & Maxillofacial Implants*, *35*(6), 1159–1169. https://doi.org/10.11607/jomi.7942

Guentsch, A., An, H., & Dentino, A. R. (2022). Precision and trueness of computer-assisted implant placement using static surgical guides with open and closed sleeves: An in vitro analysis. *Clinical Oral Implants Research*, *33*(4), 441–450. https://doi.org/10.1111/clr.13904

Guentsch, A., Sukhtankar, L., An, H., & Luepke, P. G. (2021). Precision and trueness of implant placement with and without static surgical guides: An in vitro study. *The Journal of Prosthetic Dentistry*, *126*, 398–404. https://doi.org/10.1016/j.prosdent.2020.06.015

Hämmerle, C. H. F., & Tarnow, D. (2018). The etiology of hard- and soft-tissue deficiencies at dental implants: A narrative review. *Journal of Clinical Periodontology*, *45*(Suppl 20), S267–S277. https://doi.org/10.1111/jcpe.12955

ISO-5725-1:1994(E). (2018). Accuracy (trueness and precision) of measurement methods and results - part 1: General principles and definitions. Geneva: International Organization for Standardization. *ISO Store Order: OP*-449776 (Date: 2020-06-18). http://www.iso.org/iso/home.html

Joda, T., Derksen, W., Wittneben, J. G., & Kuehl, S. (2018). Static computer-aided implant surgery (s-CAIS) analysing patient-reported outcome measures (PROMs), economics and surgical complications: A systematic review. *Clinical Oral Implants Research*, *29*(Suppl 16), 359–373. https://doi.org/10.1111/clr.13136

Jorba-Garcia, A., Gonzalez-Barnadas, A., Camps-Font, O., Figueiredo, R., & Valmaseda-Castellon, E. (2021). Accuracy assessment of dynamic computer-aided implant placement: A systematic review and meta-analysis. *Clinical Oral Investigations*, *25*(5), 2479–2494. https://doi.org/10.1007/s00784-021-03833-8

Koop, R., Vercruyssen, M., Vermeulen, K., & Quirynen, M. (2013). Tolerance within the sleeve inserts of different surgical guides for guided implant surgery. *Clinical Oral Implants Research*, *24*(6), 630–634. https://doi.org/10.1111/j.1600-0501.2012.02436.x

Laederach, V., Mukaddam, K., Payer, M., Filippi, A., & Kuhl, S. (2017). Deviations of different systems for guided implant surgery. *Clinical Oral Implants Research*, *28*(9), 1147–1151. https://doi.org/10.1111/clr.12930

Lou, F., Rao, P., Zhang, M., Luo, S., Lu, S., & Xiao, J. (2021). Accuracy evaluation of partially guided and fully guided templates applied to implant surgery of anterior teeth: A randomized controlled trial. *Clinical Implant Dentistry and Related Research*, *23*(1), 117–130. https://doi.org/10.1111/cid.12980

Mozer, P. S. (2020). Accuracy and deviation analysis of static and robotic guided implant surgery: A case study. *The International Journal of Oral & Maxillofacial Implants*, *35*(5), e86–e90. https://doi.org/10.11607/jomi.8231

Putra, R. H., Yoda, N., Astuti, E. R., & Sasaki, K. (2022). The accuracy of implant placement with computer-guided surgery in partially edentulous patients and possible influencing factors: A systematic review and meta-analysis. *Journal of Prosthodontic Research*, *66*(1), 29–39. https://doi.org/10.2186/jpr.JPR_D_20_00184

Raico Gallardo, Y. N., da Silva-Olivio, I. R. T., 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*(5), 602–612. https://doi.org/10.1111/clr.12841

Ramanauskaite, A., Becker, J., Sader, R., & Schwarz, F. (2019). Anatomic factors as contributing risk factors in implant therapy. *Periodontology 2000*, *81*(1), 64–75. https://doi.org/10.1111/prd.12284

Sittikornpaiboon, P., Arunjaroensuk, S., Kaboosaya, B., Subbalekha, K., Mattheos, N., & Pimkhaokham, A. (2021). Comparison of the accuracy of implant placement using different drilling systems for static computer-assisted implant surgery: A simulation-based experimental study. *Clinical Implant Dentistry and Related Research*, *23*(4), 635–643. https://doi.org/10.1111/cid.13032

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. https://doi.org/10.1111/jcpe.13160

Tahmaseb, A., Wu, V., Wismeijer, D., Coucke, W., & Evans, C. (2018). The accuracy of static computer-aided implant surgery: A systematic review and meta-analysis. *Clinical Oral Implants Research*, *29*(Suppl 16), 416–435. https://doi.org/10.1111/clr.13346

Tatakis, D., Chien, H., & Parashis, A. (2019). Guided implant surgery risks and their prevention. *Periodontology 2000*, *2000*(81), 194–208. https://doi.org/10.1111/prd.12292

Tattan, M., Chambrone, L., Gonzalez-Martin, O., & Avila-Ortiz, G. (2020). Static computer-aided, partially guided, and free-handed implant placement: A systematic review and meta-analysis of randomized controlled trials. *Clinical Oral Implants Research*, *31*(10), 889–916. https://doi.org/10.1111/clr.13635

Van Assche, N., & Quirynen, M. (2010). Tolerance within a surgical guide. *Clinical Oral Implants Research*, *21*(4), 455–458. https://doi.org/10.1111/j.1600-0501.2009.01836.x

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*(1), 214–227. https://doi.org/10.1111/prd.12056

Vercruyssen, M., Hultin, M., Van Assche, N., Svensson, K., Naert, I., & Quirynen, M. (2014). Guided surgery: Accuracy and efficacy. *Periodontology 2000*, *66*(1), 228–246. https://doi.org/10.1111/prd.12046

Yeung, M., Abdulmajeed, A., Carrico, C. K., Deeb, G. R., & Bencharit, S. (2020). Accuracy and precision of 3D-printed implant surgical guides with different implant systems: An in vitro study. *The Journal of Prosthetic Dentistry*, *123*(6), 821–828. https://doi.org/10.1016/j.prosdent.2019.05.027

Younes, F., Cosyn, J., De Bruyckere, T., Cleymaet, R., Bouckaert, E., & Eghbali, A. (2018). A randomized controlled study on the accuracy of free-handed, pilot-drill guided and fully guided implant surgery in partially edentulous patients. *Journal of Clinical Periodontology*, *45*(6), 721–732. https://doi.org/10.1111/jcpe.12897

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*(1), 28–40. https://doi.org/10.1016/j.jebdp.2017.07.007

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