Accuracy and Precision of Haptic Robotic-Guided Implant Surgery in a Large Consecutive Series

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Purpose: To determine the accuracy of dental implant placement using haptic robotic guidance in a large clinical series. ***Materials and Methods:*** In a prospective single-arm clinical study, 108 patients received 273 individual endosteal implants. A virtual preoperative restorative and surgical plan was created from a CBCT scan and matched to the surgical workspace on the day of surgery via either a tooth-based or bone-based fiducial splint. Intraoperatively, the surgeon manipulated a handpiece attached to a haptic robotic guidance arm. A variety of drills and implants were used. Both the osteotomy and the implant placement were guided by 3D haptic constraints according to the virtual plan. Postoperative CBCT scans permitted the calculation of the actual implant placement deviations compared to the plan for accuracy. Precision was calculated by comparing SDs from published literature. ***Results:*** The implants were evenly distributed by arch, with 47% placed in the maxilla and 53% in the mandible. The mean ± SD signed depth deviation was 0.14 ± 0.87 mm proud. The global angular deviation averaged 1.42 ± 1.53 degrees, with 95% confidence limits of 1.24 and 1.60 degrees. The crown of the actual placed implant showed an average deviation from the plan of 1.10 ± 0.69 mm and the apex of the placed implant showed a deviation of 1.12 ± 0.69 mm. Haptic robotic guidance showed greater precision than freehand, static computer-guided, and dynamic computer-guided implant placement. ***Conclusions:*** This large clinical series of 273 implants shows a high accuracy of implant placement compared to the published accuracy for angular deviations for any technology, as well as demonstrating statistically greater precision. Long-term clinical studies are necessary to establish the true effect of increased accuracy on clinical outcomes. Using haptic robotic guidance provides accurate implant placement while allowing additional benefits compared to computer-guided surgery, namely full visualization of the surgical field and the ability to change the plan intraoperatively. *Int J Oral Maxillofac Implants 2024;39:99–106. doi: 10.11607/jomi.10468*

Keywords: robotics, dental implant, haptics, accuracy

The introduction of CBCT has improved dental implant treatment by allowing for 3D presurgical planning that takes into account complex 3D bone geometry and quality.[1,2] Static computer-guided, dynamic computer-guided, and haptic robotic-guided surgical systems have leveraged CBCT to bring 3D preoperative planning to the execution phase in an effort to improve the accuracy of implant placement and, ultimately, clinical outcomes.

Static computer-guided systems use the 3D plan to create static physical guides to assist with either osteotomy preparation or, more recently, endosteal implant placement. The more recent systems that also guide implant placement have shown improved accuracy compared to either freehand or drill-guided methods.[3] Error can occur within several sources of static computer-guided systems, including the original scan, the 3D print of the physical guide, the fit of the guide to the mouth, and the required tolerance between the static drill guide and the drill bit.[4–10] While static computer-guided systems have routinely proven more accurate than freehand implant placement, tooth-supported templates have shown greater accuracy than mucosa-supported or bone-supported templates.[6,11,12] The limitations of static computer-guided systems include the lead time required to manufacture the guide following the plan, the possibility of guides breaking or moving during use, and the fact that static guides do not allow for intraoperative adjustments. In addition, the guides often involve stacked sleeves that require increased access, which can be challenging in posterior locations and can impede visual and irrigation access to the surgical site.[12–14]

Dynamic computer-guided systems use the 3D plan to provide real-time visual feedback of the drill or implant position relative to the plan. The accuracy of dynamic computer-guided systems has been shown to be similar to static computer-guided systems.[12,14] Dynamic computer-guided systems obviate several of the limitations of static systems by allowing for direct surgical

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Submitted January 21, 2023; accepted May 19, 2023.

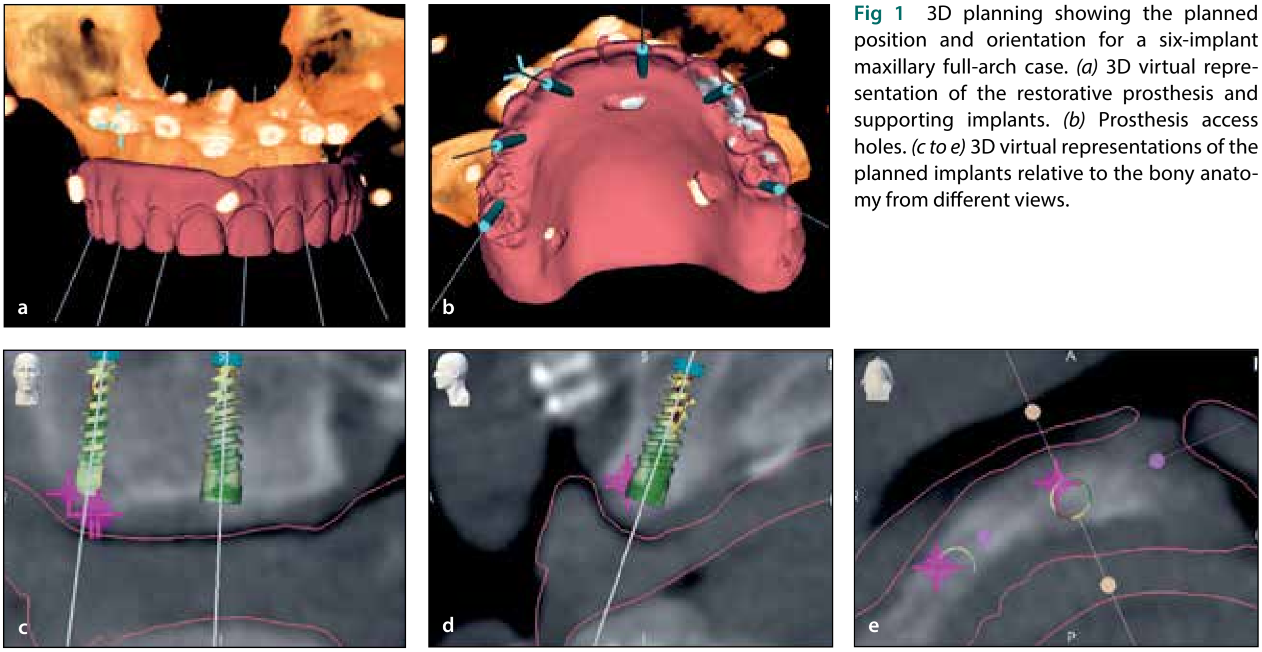


Fig 1 3D planning showing the planned position and orientation for a six-implant maxillary full-arch case. *(a)* 3D virtual representation of the restorative prosthesis and supporting implants. *(b)* Prosthesis access holes. *(c to e)* 3D virtual representations of the planned implants relative to the bony anatomy from different views.

site access, intraoperative plan adjustments, and same-day treatments. However, dynamic computer-guided systems do not physically guide the execution of the procedure to prevent the tools from deviating from the plan, but instead provide visual feedback of this deviation. A limitation of camera-based, dynamic computer-guided systems is the requirement of an uninterrupted line of sight between the stereoscopic camera system and the tracked tools.[13]

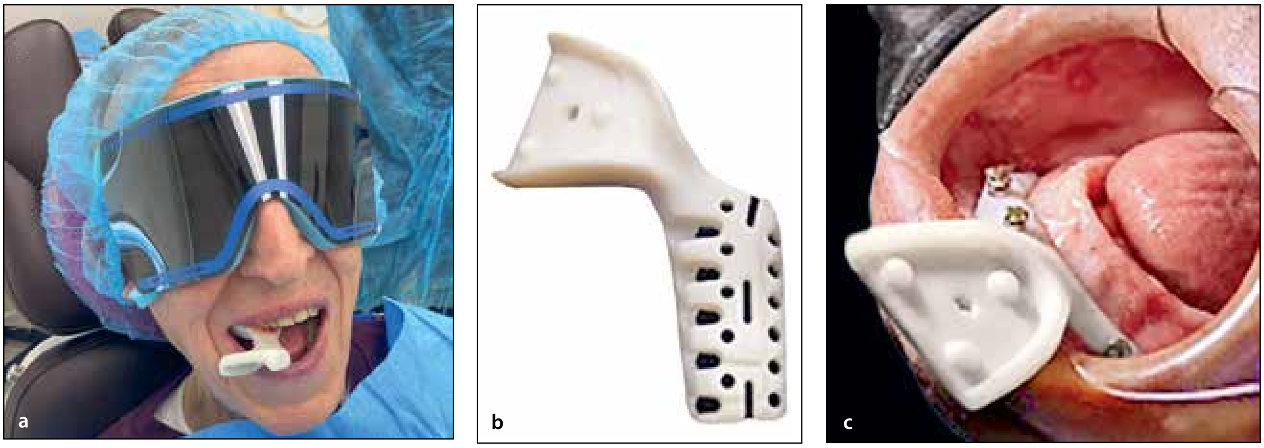
Haptic robotic-guided systems use the 3D plan to provide real-time visual and physical feedback to provide the static computer-guided benefit of physical constraint and the dynamic computer-guided benefits of same-day surgery and intraoperative flexibility without the methods' respective drawbacks. The first FDA-cleared commercially available haptic robotic-guided system for dental implant surgery (Yomi, Neocis) is drill- and implant-agnostic—that is, there is not a Yomi-specific drill and implant set that must be used. The robotic system can be used with any drill and implant, allowing surgeons to use whatever system they are most comfortable with and best fits the clinical needs to the patient. The haptic boundaries provide 3D physical guidance of the surgical instruments during both drilling and implant placement in terms of location, angulation, and depth. Haptic robotic-guided implant placement has been shown to be at least as accurate as both static and dynamic computer-guided systems.[15] However, that study was limited in size, as it reported on 38 implants in five fully edentulous patients in the initial fully edentulous clinical study submitted for FDA approval.

These technologies have been developed to improve the accuracy and precision of freehand dental implant placement. Accuracy is important in implant dentistry for obvious esthetic reasons, but also to avoid intraoperative complications, as implants are often placed in close proximity to vital nerve and vessel structures.[16] Inaccuracies can also lead to postoperative issues related to the prosthesis, patient discomfort, and implant longevity.[17,18] The purpose of this study was to evaluate the 3D accuracy and precision of individual implant placement using haptic robotic guidance in a large clinical series.

MATERIALS AND METHODS

This research protocol was approved and administered under a Western IRB exemption. In a prospective single-arm clinical study, 273 individual implants were placed in 108 patients (41 men, 67 women; average age: 57 years; range: 19 to 92 years) from August 2020 to August 2022. The inclusion criteria were:

- The implant procedure was performed with haptic robotic guidance on patients consistent with the indications for use.
- The anatomical landmark check registered the scan with the physical space passed upon start of the procedure.
- The implant placement was robotically guided to at least 50% of the planned depth.



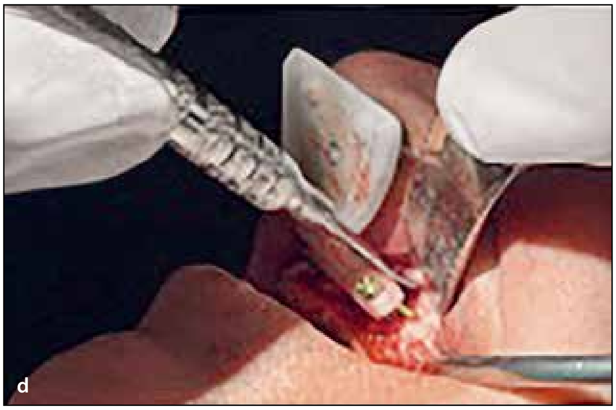


Fig 2 Single-use injection-molded tooth-based and bone-based splints for attachment to the integrated kinematic tracking mount. *(a)* Patient undergoing CBCT with an affixed tooth-based splint containing radiopaque fiducials. *(b)* Injection-molded splint showing the kinematic tracking arm mount. *(c and d)* Bone-based splint with a kinematic mount.

- Postoperative CBCT was obtained for analysis for the day of the surgery.
- All implants were placed by a single surgeon (J.M.N.).

The exclusion criteria were:
- Any off-label use or system/device modifications.
- Implants hand-driven to more than 50% of their planned depth.
- Patients whose splint did not remain stable throughout the procedure.

The implants were evenly distributed by arch, with 47% placed in the maxilla and 53% in the mandible. All cases, regardless of the number of implants, were performed in a single day. The distribution of implants was 120 BLX implants (Straumann), 55 NobelActive implants (Nobel Biocare), 47 Prima Plus implants (Keystone Dental Group), 42 Paltop implants (Keystone Dental Group), and 9 External Hex Co-Axis implants (Southern Implants).

Before the procedure, a preoperative CBCT scan was obtained and a virtual preoperative restorative and surgical plan was created (Neocis; Fig 1). This scan and planning could take place before the day of surgery or the day of surgery. On the day of surgery, a single-use, disposable splint was used to register the preoperative plan to the surgery space. A combination of tooth-based and bone-based splints were used in this patient series (Fig 2). The tooth-based splints were affixed to the remaining teeth on the anterior maxilla or anterior mandible using Ufi Gel Hard C (VOCO). The bone-based splints were affixed to the anterior maxilla or mandible with self-tapping bone screws (2.0- or 2.3-mm diameter, Stryker). A CBCT scan was then taken with a splint-mounted fiducial array that allowed the previously created virtual plan to be merged with the day-of-surgery scan, such that the haptic boundaries defined by the plan were registered to the patient's anatomy. The fiducial array was then removed from the splint and replaced with a flexible patient-tracker arm affixed to the robot (Yomi) that allowed the robotic software to track the patient's motion. This technology enabled the 3D plan that the robotic arm implemented to dynamically move with the patient during the procedure, obviating the need to either immobilize the patient or use infrared cameras that required uninterrupted line of sight. Intraoperatively, the surgeon (J.M.N.) maneuvered the robotic handpiece attached to the robotic guidance arm. As this was an implant-agnostic system, the drills or burs specific to that implant system were affixed to the implant-agnostic robotic handpiece. The robot and software allowed for a wide variety of osteotomy tools and implants to be used. The guidance arm haptically constrained the handpiece in 3D space as defined by the virtual plan while the surgeon performed the osteotomies and placed the implants. The haptic boundaries constrained the osteotomy and the

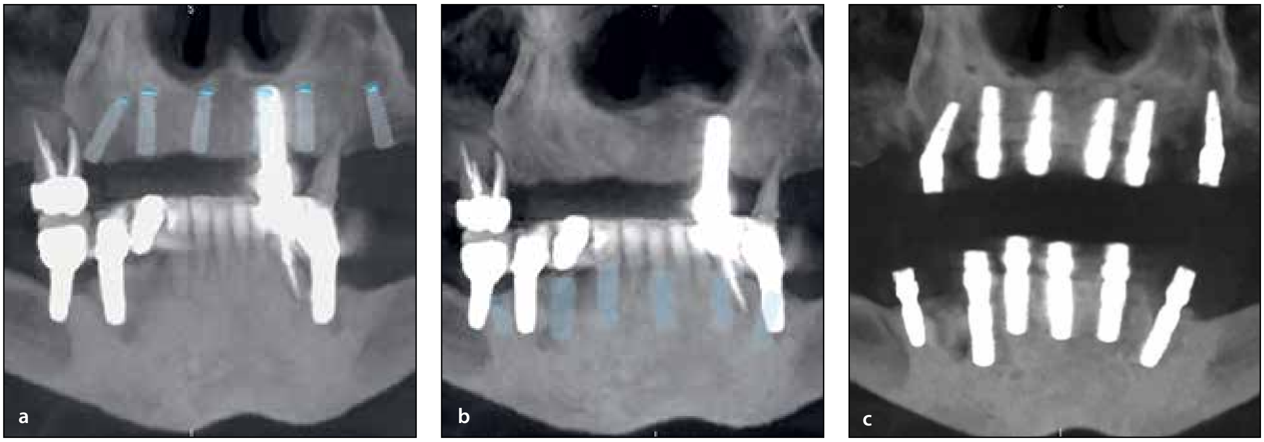


Fig 3 Preoperative CBCT scan showing the planned positions for implants in *(a)* the maxilla and *(b)* the mandible compared to *(c)* the postoperative CBCT scan showing the final actual implant positions.

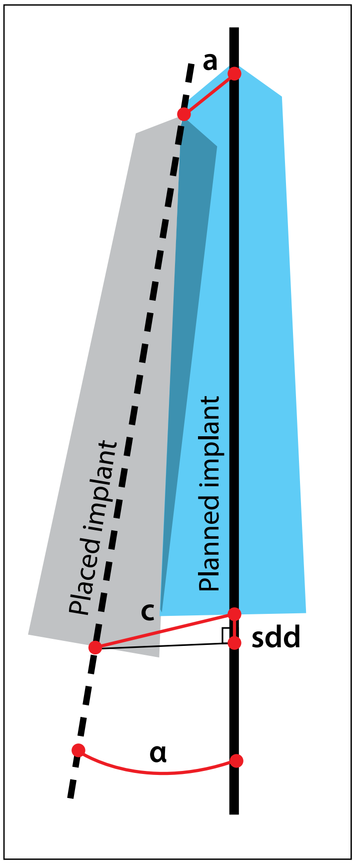


Fig 4 Representation of implant accuracy parameters: global angular deviation (α), signed depth deviation (sdd), global coronal deviation (c), and global apical deviation (a). All measurements were recorded in millimeters except for the global angular deviation, which was recorded in degrees.

implant placement location, angulation, and depth. The patient-tracker arm allowed the patient to move while the haptic boundaries dynamically tracked the patient's motion. To ensure registration was maintained throughout the procedure, a landmark check process was performed at the beginning and end of every case. If the landmark did not align, an additional CBCT scan was taken to verify proper prosthetic position.

Patients then received a postoperative CBCT scan on the day of surgery to assess the implant placement accuracy relative to the plan. The implant accuracy was measured using a standardized 3D voxel-to-voxel–based registration of the postoperative CBCT scan superimposed onto the preoperative CBCT scan using isosurface matching of localized regions with an iterative closest-point algorithm[7,19,20] (Fig 3). While not used to match the bone regions, the preoperative virtual plan overlay and the final implant positions were transformed with the preoperative and postoperative CBCTs, respectively, during the registration process. The software used in the present study has been previously validated and published.[15] Reporting deviations between the planned and actual location of each implant was standardized in the International Team for Implantology (ITI) consensus report to allow for fair comparisons across studies. Deviations are reported in degrees in terms of global angular deviation (α), which is the 3D angle between the central axis of the planned and the placed implants, and in millimeters for the signed depth deviation (sdd), which is the difference in the coronal depth of the planned and placed implants along the long axis of the planned implant, with negative indicating that the actual placement is deeper than on the plan. In addition, the global coronal deviation (c) and global apical deviation (a), are both reported in millimeters. These two metrics represent the 3D distances between the coronal and apical centers of the planned and actual implant positions (Fig 4). All metrics were assessed using standard descriptive statistics (mean, SD, minimum, maximum, and 95% CI). Using an F test, precision was determined by comparing the SD of the angular measurements from the present series to published literature for all the other placement modalities.

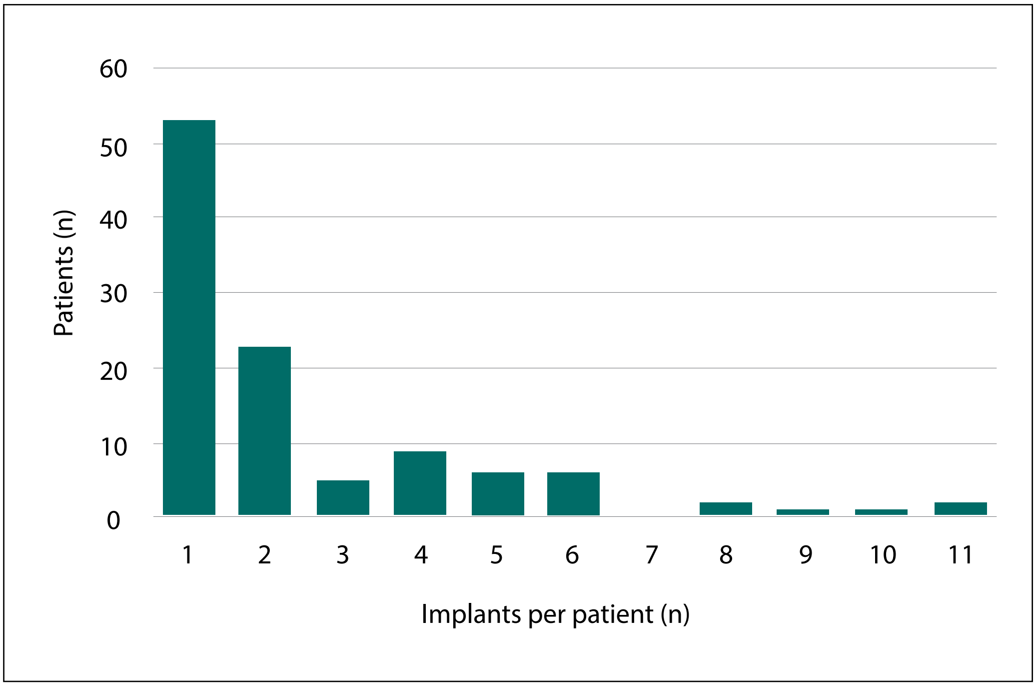


Fig 5 Distribution of number of implants per patient.

RESULTS

A total of 273 implants were placed in 108 patients, with 47% in the maxilla and 53% in the mandible. Approximately half (53/108) of the patients received a single implant, while the rest of the patients received multiple implants, with two patients receiving the study maximum of 11 implants (Fig 5). No nerve canal perforations or apical, buccal, or lingual bone penetrations were seen in the postoperative CBCT images. Accuracy was assessed by the signed depth deviation, the global angular deviation, and the 3D coronal and apical deviations (Table 1). The mean ± SD signed depth deviation was 0.14 ± 0.87 mm proud. The global angular deviation averaged 1.42 ± 1.53 degrees with 95% confidence limits of 1.24 and 1.60 degrees. The crown of the actual placed implant showed an average deviation from the plan of 1.10 ± 0.69 mm and the apex a deviation of 1.12 ± 0.69 mm. Implants placed in the mandible were on average more proud (0.32 ± 0.73 mm) than the plan compared to implants placed in the maxilla (0.03 ± 0.99 mm deep; $P = .0037$). There were no other statistically significant differences in implant deviations between the mandible and maxilla in angular, global coronal, and global apical deviations ($P = .81$, $P = .11$, and $P = .11$, respectively; Fig 6).

To compare the precision of the haptic robotic-guided technology used herein, the SDs were compared across measurements reported here and those reported in the literature for freehand implant placement,[16] static computer-guided implant placement (single supported, single bone-supported, and multiple mucosa-supported),[9] and dynamic computer-guided placement (partially with guidance of the osteotomy only and fully with guidance of both the osteotomy and the implant).[17] Haptic robotic-guided implant placement was significantly more precise than all other guidance technologies ($P < .05$; Table 2).

Table 1 Descriptive Statistics of Implant Deviations

	Signed coronal depth (sdd), mm	Angular deviation (α), deg	Global coronal deviation (c), mm	Global apical deviation (a), mm
Mean	0.14	1.42	1.10	1.12
SD	0.87	1.53	0.69	0.69
Maximum	2.85	6.61	3.28	3.56
Minimum	–2.92	0.00	0.00	0.00
Upper 95% CI	0.25	1.60	1.18	1.20
Lower 95% CI	0.04	1.24	1.02	1.04

The sample size was 273 implants.

DISCUSSION

This study on the use of haptic robotic guidance to prepare and place implants presented low implant placement errors (high accuracy) compared to the published literature across all technologies. The results from this study showed accurate implant placement in position

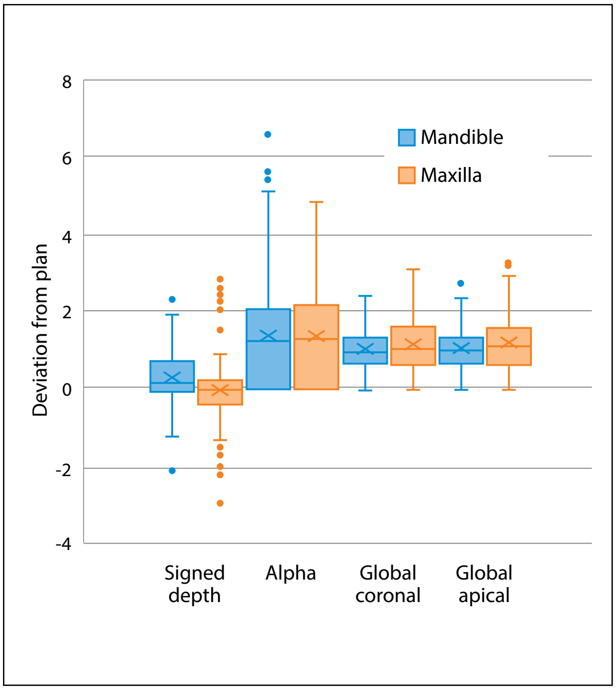


Fig 6 Box-and-whisker plot showing the deviation comparisons between the mandible and the maxilla. Signed depth, global coronal, and global apical are reported in millimeters and alpha (angular deviation) is reported in degrees.

Table 2 Comparison of SDs for Angular Deviation Across Modalities for Precision

	SD (deg)	df	F_{exp}	F_{crit} ($P = .05$)
Haptic robotic-guided (current study)	1.53	273	–	–
Static computer-guided single type, mucosa-supported (Cassetta et al[9])	3.38	54	4.88	1.38
Static computer-guided single type, screw-supported (Cassetta et al[9])	2.34	57	2.34	1.38
Static computer-guided multiple type, mucosa-supported (Cassetta et al[9])	3.70	116	5.85	1.29
Freehand (Schnutenhaus et al[16])	4.80	52	9.84	1.39
Dynamic computer-guided, partially (Block et al[17])	2.33	373	2.32	1.21
Dynamic computer-guided, fully (Block et al[17])	2.09	219	1.87	1.23

and orientation with respect to the plan. Accuracy is important in implant placement because inaccuracies can cause intraoperative issues related to interference with critical anatomic structures and postoperative issues related to prosthetic reconstruction, patient satisfaction, and implant longevity.[18,21,22] Implant accuracy is defined as the deviation of the final implant placement compared to the plan. Table 3 compares accuracy data from this study with several other studies (including several meta-analyses). While both state that computer-guided and dynamic computer-guided technologies have improved the accuracy of implant placement compared to freehand techniques, the addition of haptic robotic guidance has further improved the accuracy, particularly in angular deviation, with the deviations reported herein showing the lowest mean of any published implant placement accuracy study. Haptic robotic guidance also proved to be significantly more precise than all other placement modalities, including freehand placement and static computer-guided and dynamic computer-guided placement.

One explanation for haptic robotic guidance resulting in approximately half of the angular errors along the implant axis than the number reported for both static and dynamic computer-guided devices might lie in the geometry and distribution of the bone density in the prepared bed. Haptic robotic guidance provides not only visual guidance but also stiff 3D physical constraints of the handpiece (either drill or implant) along the implant axis, preventing skiving (wandering) of the tool. As the global coronal and apical positional deviations are similar amongst the technologies, the angular errors with nonrobotic technology are somewhat distributed along the length of the implant. The author is not aware of any studies that compare the accuracy of technologies between bone preparation and implant placement in the same patient; thus, it is currently not possible to determine whether the additional angular inaccuracies in static computer-guided and dynamic techniques occur with drilling, implantation, or both. Haptic robotic placement does not have the fulcrum effect that static guides have shown, where the apical deviations tend to be greater than the coronal deviations.[25] This improvement in angular accuracy might further protect against placing implants in vital structures, such as the sinus, nerves, or adjacent tooth roots. Of course, as with any other technology, proper clinical oversight and judgment must always be exercised. Advanced technology and devices do not replace clinical decision-making, but rather augment execution.

This paper demonstrates that the most accurate form of implant placement is realized using haptic robotic-guided technology. A limitation of this paper is that it only reports on implant placement accuracy and not clinical or survival outcomes. While it is generally agreed that accuracy is important in implant placement for obvious safety reasons, the minimal clinically important difference has not been established for either

Table 3 Comparison to Published Studies

	Implants	Technology	Signed coronal depth (sdd), mm	Angular deviation (α), deg	Global coronal deviation (c), mm	Global apical deviation (a), mm
Current study	273	Haptic robotic-guided	0.14 (0.04 to 0.25)	1.42 (1.24 to 1.60)	1.10 (1.02 to 1.18)	1.12 (1.04 to 1.21)
Tahmeseb et al[7]	Meta; 2,238	Static computer-guided	0.20 (–0.25 to 0.57)	3.50 (3.00 to 3.96)	1.20 (1.04 to 1.44)	1.40 (1.28 to 1.58)
Block et al[17]	219	Dynamic computer-guided (fully)	0.76 ± 0.60	2.97 ± 2.09	1.16 ± 0.59	1.29 ± 0.65
Block et al[17]	373	Dynamic computer-guided (partially)	0.89 ± 0.73	3.43 ± 2.33	1.31 ± 0.68	1.52 ± 0.78
Schneider et al[22]	Meta; 321	Static computer-guided	0.43 (0.12 to 0.74)	5.26 (3.94 to 6.58)	1.07 (0.76 to 1.22)	1.63 (1.26 to 2.00)
Vercruyssen et al[23]	Meta; 279	Static computer-guided	0.5 (0.2 to 0.7)	3.8 (3.2 to 4.4)	1.0 (0.8 to 1.2)	1.2 (1.0 to 1.6)
Guzman et al[24]	20	Dynamic computer-guided	NR	4.00 ± 1.41	0.85 ± 0.48	1.18 ± 0.60

NR = Not reported.
Values reported as mean (95% CI) or mean ± SD.

implant accuracy or precision. There is a question that arises in surgical technology aimed at reducing outliers and improving accuracy, which is: "How accurate is accurate enough?" In other words, if two cohorts using two different technologies with differing levels of accuracy prove to have the same the functional outcomes and longevity, what should be the determining factor for which technology to use? Should cost, efficiency, and patient preference play a role, or is greater accuracy always better? Before this becomes a topic of discussion, advanced randomized clinical trials tracking functional outcomes and longevity should be performed. The other collateral benefit of improved accuracy and predictability is the potential to perform procedures less invasively, allowing implants to be placed immediately following extraction, primarily due to the confidence in knowing the final seated implant position will be accurate compared to the plan. Another limitation of this study is that no comparative cohort was included. However, this was one of the larger series of clinical placements and represented a consecutive series. There is an abundance of published literature on the accuracy of other guidance technologies, and the standardization of error reporting makes comparison with a single series valid and valuable.

CONCLUSIONS

The haptic robotic-guided technology used in this study was implant-agnostic, thereby maximizing potential utilization. However, as technology continues to improve, the accuracy, reliability, and predictability of implant placement will approach and surpass the the variability that exists in prosthetic componentry. Currently, prosthetic componentry has intentionally been designed with flexibility to account for variability in implant placement. While these clever design features result in optimal final esthetics and functional reconstruction, these features also add significant complexity and cost to the array of prosthetic components. Once optimal implant accuracy provides completely predictable 3D placement, the potential arises to redesign prosthetic components to be more simple, less costly, and more efficient. This is a worthy goal and will represent the success of technology's long attempt to close the surgical/prosthetic gap, thus minimizing the burden on the reconstruction and design of prosthetic components.

ACKNOWLEDGMENTS

The author declares no conflicts of interest.

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