Evaluation of the Accuracy of a New Geometric Approach to Implant Guidance

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Purpose: Implant surgical guides are often fabricated using CBCT technology. In this study, an alternative technique is proposed. The aim of this in vitro study was to compare the accuracy of the guide sleeve corrections of a geometric approach to guided surgery to the accuracy of in vitro studies of stereolithographic guides. Materials and Methods: Four arch forms were milled from acrylic blocks each with 12 root form sites. Root form inserts were made. Holes were milled in the inserts at arbitrary angles. Guide posts were placed in these sites. Guide sleeves were placed on the posts and connected with light-cured resin to form verification jigs. The goal was to correct the angles of the guide sleeves to a vertical position 90 degrees from the base of the arch forms. The initial angles from the vertical and horizontal positions of the center of each guide sleeve were determined radiographically and geometrically. Horizontal and angle corrections were made using two-piece guide posts. Guide sleeves placed over the corrected guide posts were connected with light-cured resin, forming new verification jigs. The accuracy of the angle correction and the coronal horizontal and apical horizontal deviations of the 3-mm guide sleeves were determined. The experimental sites were divided into two groups to determine if the size of the initial angles of the guide sleeves had any effect on the accuracy of the corrections. Results: The initial angles of the guide sleeves before corrections revealed the mean difference between the two methods of measurements in groups 1 and 2 as 0.36 degrees ($P = .14$) and 0.69 degrees ($P = .07$), respectively. A comparison of the angle error measurements from 90 degrees after corrections between the two groups in the mesiodistal and buccolingual planes was not significant. The coronal and apical horizontal deviations after corrections revealed a significant difference between the two groups at the coronal level ($P = .05$) but not at the apical level ($P = .14$). In comparison of the methods of the two measurements of the angle error from vertical after corrections, the mean difference was 1.23 degrees ($P = .01$) and 0.69 degrees ($P = .02$). Conclusion: The in vitro accuracy of the guide sleeve corrections made with the geometric approach for implant guidance was compared to the results of the meta-analyses of in vitro studies of implant placement with stereolithographic guides. The mean errors were smaller and within the recommendations of the EAO Consensus Conference of 2012. Int J Oral Maxillofac Implants 2022;37:104–113. doi: 10.11607/jomi.9205

Keywords: guidance, guidepost, single implant, surgical guide, surgical procedure

Surgical guides utilized during implant placement have become routine in usage, making implant placement more predictable and allowing a prosthetic guided approach to be utilized.1 The surgical guide acts as a template, providing guidance of the osteotomy drills at the correct ridge position, angulation, and depth, to avoid anatomical structures that could be damaged during freehand implant placement, thereby decreasing the risk of iatrogenic damage of anatomical structures. Further, it acts as an aid in the accuracy of treatment planning, permitting implant placement based on a prosthetic designed plan, assuring adequate implant spacing with esthetic placement to allow proper maintenance and hygiene.2 This becomes more critical when treating the edentulous arch, as visible landmarks that could aid in guiding the osteotomy (ie, teeth) are not present, and orientation to underlying anatomical structures is lost. Evaluation of radiographs is used to guide the osteotomy, where typically a surgical guide was not used. This consisted of panoramic and periapical radiographs, with the surgeon using that information for freehand placement.3 CBCT has permitted better implant placement guidance with the fabrication of surgical guides that is based on the anatomy present and fully guiding the implants based on a prosthetic oriented plan.4–6 The risk of anatomical damage

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is also greatly diminished, as the “hidden” anatomical structures are visualized in the CBCT during virtual planning. A flapless approach to surgical placement is permitted with a CBCT-guided surgical stent, making surgery less traumatic and healing easier for the patient. This becomes more critical as the jaws undergo greater degrees of atrophy with zygomatic and pterygoid implants being planned.

Computer-milled stereolithographic surgical guides are commonly used, as they provide 3D guidance for the placement of implants. Accuracy is improved in placement, which translates into elimination of prosthetic complications related to implant position that often arise in freehand placement of implants. As mentioned, this becomes more critical in the edentulous arch. Studies evaluating the accuracy of surgical guides have shown that stereolithographic surgical guides are more accurate than surgery completed with stone model–based guides or freehand surgery. However, the limitations of using stereolithographic surgical guides are additional cost and time delay to fabricate the surgical guide. Vacuum-formed matrix surgical guides based on a prosthetic plan may result in inaccurate angulation or placement of the implant. Therefore, more precise positioning and expedient correction of drill guides is desirable. It is pertinent to mention that both horizontal and angular adjustments are often necessary in developing the correct surgical guide. In this in vitro study, an alternative technique is proposed that utilizes manual angle and horizontal corrections determined with the Invivo5 software (KaVo Dental). It indicates the appropriate global position of an implant position chosen by the operator and directed by the surgical guide sleeve. As angle and horizontal corrections are dependent upon the software, the accuracy of the software should be evaluated. In vitro studies have been shown to be more accurate than clinical studies. Possible reasons include better access, no patient movement, no blood, and no saliva. Computer-guided implant placements can be accurate, but significant deviations must be considered. The accuracy of computer-aided implant surgery is within the clinically acceptable range in the majority of clinical situations. However, a safety margin of at least 2 mm should be respected.

The aim of the present study was to evaluate the accuracy of a geometric approach to guided surgery in an in vitro model. Additionally, this study compared the accuracy of the i-CAT/Invivo5 method with an alternative 3D coordinate measuring machine (CMM) method of determining angle and linear measurements. In 3D radiographic imagery, although it allows planning based on the anatomical structures present, the prosthetic aspect is lacking with current virtual planning, which can create challenges when the prosthetic phase of treatment is initiated. A geometric approach utilizes that prosthetic planning with regard to surgical guide design based on virtual planning.

MATERIALS AND METHODS

The following components were used in this study: acrylic arch forms, root form inserts, guide posts, guide sleeves, verification jigs, horizontal and angular evaluation, and corrections of the guide sleeves and posts. To achieve the goals of this study, a computed tomography machine (i-CAT FLX, Imaging Sciences International), computer-based software (Invivo5), and a CMM industrial measuring device for 3D visualization and inspection were used. To take measurements, a Leitz scanning probe (Hexagon Metrology) and PC-DMS CAD software (Hexagon Manufacturing Intelligence) were incorporated.

The arch forms each made from acrylic blocks (89 × 127 × 33 mm) were designed to represent a dental arch. Twelve test sites (machined holes) were created in each arch form with six additional parallel sites medial to the test sites for six additional parallel guide posts (Fig 1a). Root form inserts were developed in two sizes to represent implant sites for smaller- and larger-diameter teeth. They had a 6.35-mm outer diameter (OD) or 9.5 mm (OD) The cylindrical inserts were made from polyether ether ketone (PEEK), a machineable plastic. Holes were milled into the top of the inserts (2.38 mm OD × 11 mm deep) made at a variety of angles (Fig 1b). The holes were milled and threaded in the bottom of the inserts parallel to their long axes to accommodate a hex-headed screw used to draw the root form inserts into the holes in the arch forms and tightened with a lock washer to prevent rotation (Fig 1b). Straight guide posts (top 20 mm of post: 2.98 mm OD and lower 10 mm end of post: 2.39 mm OD) were used to align 3.1 mm inner diameter (ID) × 8 mm guide sleeve cylinders, with the long axis of the 2.39-mm holes milled in the root form inserts and guide sleeves (3.1 mm ID) being placed on the upper shaft of the guide posts (Fig 1c).

Fabrication of Verification Jigs

Verification jigs (V-jigs) were fabricated by connecting the 18 3.02-mm guide sleeves on each arch form with light-cured resin (Triad Gel, Dentsply Sirona), which was applied to connect the guide sleeves to form the V-jig (Fig 1d). Twelve guide sleeves were placed on the guide posts of the test sites and six on the aligning six parallel guide posts, which were located medial to the test sites for the purpose of supporting the V-jig while a computed tomography (CT) scan was taken (Fig 1e). The metal guide posts were removed while the V-jigs maintained the original angles of the cylindrical guide sleeves for...
a CT scan supported by the six parallel DuPont Delrin radiolucent guide posts (Figs 1d and 1e). CT scans were taken of the V-jigs, and the resulting DICOM files were then imported into the Invivo5 software. Arch form images were aligned vertically and horizontally within the software (Fig 2).

Evaluations of the Initial Angles of the Guide Sleeves in Arch Form E3 Site #20

Evaluations of the initial angles of the guide sleeves were determined with the Invivo5 software using the following protocol. A 3-mm virtual implant was selected, positioned, and aligned with the long axis of the guide sleeve in the buccolingual and mesiodistal planes (Figs 3a to 3c). The axial plane indicator (yellow A-B line; Fig 3a) was rotated buccolingually until the angle formed between the y-axis of the grid (the long axis of the implant) and the base of the arch form indicated the greatest value observed in the mesiodistal plane (Fig 3c). At the same time, the y-axis of the coordinate grid approached vertical in the buccolingual plane (90.5 degrees to the base of the arch form; Fig 3b). The angle observed in the mesiodistal plane was used to represent the greatest initial angle of the guide sleeve from the vertical (120 – 90 = 30 degrees; Fig 3c).

CMM is a measuring device for 3D visualization and inspection, with accuracy to a level of 1.9 µm, which complied with ISO 10360-2 geometric specifications and uses a scanning probe and PC-DMIS CAD++ software. Evaluation of the accuracy of the radiographic angle measurements was done with the i-CAT and evaluated with the Invivo5 software. Measurements of the greatest angles of the guide sleeves were also evaluated geometrically with a CMM and PC-DMIS CADV++ software. To measure the angles of the guide sleeves with the CMM, gauge pins (3.02 mm OD) were placed in the 3.03-mm guide sleeves of the 12 test sites on the V-jigs. The angles of the gauge pins were measured with three hits of a 1-mm probe with the CMM. The angles were determined with the PC-DMIS CAD software.

Evaluations and Corrections of the Horizontal Deviations with the Invivo5 Software

The horizontal deviations, length, and radial direction from the center of the root form inserts were determined using the Invivo5 software. To determine the horizontal corrections required, the distance and direction from the center of the 2.39-mm holes in the root form inserts to the center of the PEEK inserts were measured. The most appropriate two-piece offset guide post was selected and used to make horizontal corrections to reposition the guide sleeves. The most appropriate offset guide posts were selected to make
the horizontal correction, utilizing components of the Guide Right 2-Piece Guide Post (DePlaque; Fig 4)

The octagonal lower shaft, a 10-mm-long × 2.4 mm OD shaft, has eight flat sides, enabling the corrections to be made in eight different directions corresponding with the surfaces of a tooth. The upper shaft (1.6 mm OD × 5 mm long) of the offset guide post extends vertically. A rectangular platform (4 mm wide × 1.5 mm thick) is located below the upper shaft, allowing the upper shaft to be offset from the lower shaft. Just below the rectangular platform is the bending point, a narrow section of the neck where the bend occurs to make the correction close to the level of the alveolar crest in a clinical situation. The 3 mm OD × 1.61 mm (1/16 inch) ID removable top cylinder fits over the 1.60 mm (1/16 inch) OD small upper shaft of the offset guide post to center and align the 3.1-mm guide sleeve (Figs 4 and 5). The 1.6-mm upper shaft of the guide post is either aligned with the octagonal lower shaft as in a straight guide post or offset from the lower shaft in 0.5-mm intervals: 0 to 3.5 mm (Fig 4).

Angle Corrections
The angle corrections to the two-piece guide posts were made with a Guide Right Bending Tool (DePlaque; Fig 6). This was performed by inserting the guide post into the stylus. The octagonal lower shaft extending from the stylus was then inserted into the hole in the block of the bending tool. The set screw was tightened against the flat surface of the guide post to prevent rotation while the bend was accomplished. The angle correction was then made below the rectangular platform at the bending point of the guide post by moving the stylus right or left to make the correction to the appropriate degree indicating the correction required (Fig 7). A protractor was placed over the stylus to check the accuracy of the angle.

Horizontal Corrections
The direction of the horizontal correction was categorized as one of the eight anatomical descriptions of the tooth: mesial, mesiobuccal, midbuccal, distobuccal, middistal, distolingual, midlingual, or mesiolingual. The direction of the horizontal corrections was recorded

Fig 3 Invivo5 software composite view of an arch form E3 site #20 to evaluate the initial angles of the guide sleeves. (a) Axial view of the A-B (yellow) line indicating the buccal-lingual plane observed. (b) Cross-sectional view of the buccolingual plane with virtual implant aligned with the guide sleeve. (c) Tangential view of the mesiodistal plane indicating initial alignment with the guide sleeve.

Fig 4 Two-piece offset guide posts (DePlaque) utilized to make horizontal and angle corrections.

Fig 5 Two-piece offset guide post (diagram of parts): Octagonal lower shaft has eight sides for horizontal and vertical correction in eight anatomical directions.
at the coronal level so the correction of the two-piece guide posts and the 3.03-mm guide sleeves could be repositioned at the center of the coronal surface of the root form insert (Fig 8a). To determine the accuracy of the horizontal corrections, the horizontal, coronal, and horizontal apical deviations were measured in the axial images of the Invivo5 software. The most appropriate offset guide posts (Fig 4) were selected to bring the center of the 3-mm guide post to the center of the root form insert. A 3-mm guide sleeve (3.1 mm ID × 8 mm long) was placed on the 3.0-mm upper removable cylinders of the corrected two-piece guide posts and on the six parallel Delrin radiolucent guide posts (Fig 8b). The corrected guide posts with guide sleeves were inserted into each site until the rectangular platform was close to the upper (coronal) surface of the root form insert.

**Post-Correction V-Jigs**

Light-cured resin (Triad Gel) was added to connect the 12 guide sleeves to form the post-correction V-jig. The upper removable 3-mm cylinders on the two-piece guide posts were then removed to accommodate removal of the V-jig from the arch form. The lower portion of the angle and offset corrected guide posts were removed from the arch forms to reduce scatter. The V-jig was placed back on the parallel Delrin posts for the final CT (Fig 8b).

**Evaluation of the Guide Sleeve After Angle Corrections—Software Analysis**

To measure the corrected guide sleeve angles from the vertical, an analysis was completed on the CT scans (Figs 9a to 9c); the axial plane (A-B line) was rotated until it was 90 degrees to the outer (buccal) surface of the arch form (Fig 9a). Virtual implants (3.0 × 11.0 mm), outlined in red, were positioned parallel to the long axis of the guide sleeves (Figs 9b and 9c). The y-axis of the Invivo5 software grid, which was parallel with the long axis of the virtual implant, was superimposed over the radiolucent center of the 3-mm guide sleeve in both planes. The angle between the long axis of the guide sleeve and the long axis of the virtual implant was measured for comparison.
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Group Selection and Comparison of Initial Angle Measurements

The 48 sites (12 sites per arch form) in the initial V-jigs were divided into two groups to determine if the size of the initial angles of the guide sleeves had any effect on the accuracy of the corrections. The initial angle measurements of the guide sleeves were made from the horizontal plane of the base of the arch form. The distance between the center of the guide sleeve and the center of the root form insert was measured at the coronal level with the Invivo5 software to determine the horizontal coronal deviation after the corrections for each of the sites (Table 1). The horizontal apical deviation was measured utilizing the same methodology with the Invivo5 software at the apical level of the virtual implant, 10 mm below the top of the root form insert (Table 1). The angle deviations were determined from vertical at 90 degrees to the base of the arch form after the corrections. Measurements were made with both the CMM PC-DMIS and i-CAT Invivo5. The horizontal coronal deviation, horizontal apical deviation, and the angles formed by the long axis of the 3-mm guide sleeves with the base of the arch form were determined for each group.

Statistical Analysis

A paired $t$ test was used to compare the mean values before and after corrections within each group. Two-sample $t$ tests were used to determine the mean values of the angles of the guide sleeves, with the pretreatment and posttreatment differences of the groups. All analyses were implemented with SAS 9.2 (SAS Institute).

RESULTS

Horizontal Deviation After Corrections

The horizontal coronal deviation at the top of the root form inserts was measured (Table 1). The mean horizontal coronal deviation in group 1 was 0.34 ± 0.23 mm, and for group 2, it was 0.60 ± 0.36 mm ($P = .005$). Horizontal apical deviations were measured 10 mm apical to the top of the root form inserts (Table 1). The mean horizontal apical deviation in group 1 was 0.43 ± 0.35 mm, and for group 2, it was 0.59 ± 0.40 mm. The difference between the two groups was significant at the coronal level ($P = .005$). The difference in the horizontal deviations between the two groups was not significant at the apical level ($P = .14$).

Table 1

<table>
<thead>
<tr>
<th>Horizontal deviation</th>
<th>Group 1 (mm)</th>
<th>Group 2 (mm)</th>
<th>$P$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coronal</td>
<td>No. of sites</td>
<td>Mean ± SD</td>
<td>No. of sites</td>
</tr>
<tr>
<td>21</td>
<td>0.34 ± 0.23</td>
<td>27</td>
<td>0.60 ± 0.36</td>
</tr>
<tr>
<td>Apical</td>
<td>21</td>
<td>0.43 ± 0.35</td>
<td>27</td>
</tr>
</tbody>
</table>

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Initial Angles of Guide Sleeves Before Corrections

Comparison of the radiographic and geometric methods of analysis (CMM PC-DMIS and i-CAT/Invivo5 software) was utilized to compare the initial angle of the guide sleeve before and after the corrections were made from vertical (90 degrees) from the horizontal base of the arch forms. The initial angles of the guide sleeves in group 1 of 21 sites were up to 10 degrees, and for group 2 of 27 sites, they were up to 10 to 36 degrees (Table 2). The mean angle of the measurement made of the long axis of the guide posts and sleeves in group 1 measured with CMM PC-DMIS was 6.87 ± 3.07 degrees, and in group 2, it was 21.99 ± 5.33 degrees (P = .0001). The mean angle of the measurement made of the long axis of the guide sleeves in group 1 measured with i-CAT/Invivo5 was 6.50 ± 3.40 degrees, and in group 2, it was 22.68 ± 4.96 degrees (P = .0001). The mean difference between the two methods of measurement in group 1 was 0.36 ± 1.10 degrees (P = .14), and the mean difference between the two methods of measurement in group 2 was 0.69 ± 1.88 degrees (P = .07; Table 2).

Angle Deviations from the Vertical After Corrections

The means and SDs of the angle of the guide sleeves from the vertical were determined for each group (Table 3). The angles of the long axis of the guide sleeves were determined with both CMM PC-DMIS and i-CAT/Invivo5 software. The mean angle deviation in group 1 was 2.78 ± 1.46 degrees, and in group 2, it was 2.88 ± 1.49 degrees with CMM PC-DMIS. The mean angles formed between the long axes of the guide sleeves from vertical were measured with i-CAT/Invivo5 software, with the mean angle in group 1 measured as 1.55 ± 1.11 degrees, and in group 2, it was 2.18 ± 1.54 degrees. The mean difference between the two methods after corrections in groups 1 and 2 was 1.23 ± 2.03 degrees and 0.69 ± 1.46 degrees, respectively.

DISCUSSION

There is always some deviation between the virtual planning and the actual implant placement. Many clinicians have had doubts about the usefulness and accuracy of the stereolithographic techniques.²³²⁴ Implant placements are determined by the position of the guide sleeves in the surgical guide, but it is equally important for the angle and horizontal positioning of the guide sleeves to be accurate. The comparison of the accuracy between the stereolithographic surgical guides and corrected guides that were produced with a geometric approach remains unclear. Therefore, in this study, angle and horizontal measurements were utilized to compare the geometric approach using
The mean horizontal apical deviation observed in either group 1 or group 2 was smaller than 1.7 mm and thus are within the zone limitation of 1.2 mm, larger than the horizontal coronal deviation. Consensus recommended a horizontal coronal safe distance of 1.2 mm, a maximum horizontal apical deviation of 1.7 mm, and a maximum angle deviation of 4.7 degrees.13

In recent systematic reviews of static systems, a meta-analysis study compared the accuracy of implant placement with computer-guided surgery in cadavers, in clinical patients, and in in vitro studies.27 Horizontal deviation resulted in no difference reported between the clinical studies and the cadaver studies. The deviations reported in in vitro studies were significantly smaller than in the clinical studies.34–37 A review published in 2009 suggested the increased deviations could be caused from various reasons, including access, patient movement, and restricted visualization, and has been supported in more recent reports in the literature.17,38 Therefore, the results of this study are only comparable with the results of the eight in vitro studies included in a recent meta-analysis study.17

In the present study, two methods of measurement of the guide sleeve angles (i-CAT/Invivo5 and CMM-PC DMIS) were compared before and after corrections. Using the data from i-CAT, the geometric approach with corrections was evaluated. The results demonstrated that the mean horizontal coronal deviations in group 1 were not significantly different from the deviations in group 2, resulting in a P value of .005 (Table 2). These results were within the range of the values of the eight in vitro studies reported in the literature.17 The 2012 EAO Consensus recommended a horizontal coronal safe zone limitation of 1.2 mm, larger than the horizontal coronal deviation observed in either group 1 or group 2.33 (Table 1). The mean horizontal apical deviation observed in the eight in vitro studies (0.17 ± 0.85 mm) was lower than the results of the clinical and cadaver studies. The EAO Consensus Conference of 2012 recommended an apical deviation of < 1.7 mm, and the mean apical horizontal deviations of the sites in group 1 and group 2 were smaller than 1.7 mm and thus are within the accepted deviation. While the difference between the two groups was significant in the coronal deviation, the difference was not significant in the apical deviation (Table 2). One possible explanation for the significant difference between the groups at the coronal level in this study may be that the offset guide posts used to make horizontal corrections were only available at 0.5-mm length intervals (Fig 4). However, in both groups, the mean deviation was less than the 1.7-mm horizontal safety distance recommended by the EAO. When a comparison of the angles of the guide sleeves before corrections in group 1 and group 2 were measured with both methods, the groups were significantly different (Table 2). When the initial angles of the long axis of the guide sleeves from the vertical were measured with i-CAT and compared to the measurement with CMM in both groups, the results were not significantly different. The results approached significance with P = .14 in group 1 and P = .07 in group 2 (Table 2).

The comparison angles of the guide sleeves measured with the two methods were also determined after the corrections (Table 3). The difference between the mean angle measurements of group 1 and group 2 determined with CMM were not significant (P < .082). Additionally, the difference between the mean angle measurements of the two groups determined with i-CAT were also not significant (P < .11). The mean angle deviation compared with the results reported in the meta-analysis of the eight in vitro studies was 2.39 ± 0.35 degrees. The mean angle deviation measured with i-CAT from group 1 was 1.55 ± 1.11 degrees, and in group 2, it was 2.18 ± 1.54 degrees, which was not significantly different from group 1 (P = .11). Both means were smaller than the mean from the investigation of the meta-analysis of the eight in vitro studies. When the mean angle deviations were measured with CMM and then compared to angle measurements made with i-CAT, the differences were found to be statistically significant (P = .01; Table 3). This may have been a result of the small deviations of the groups. However, when the actual apical horizontal error difference of the 1.23-degree angle is calculated theoretically using the Pythagorean theorem (10 mm by tan [2°] 0.035 = 0.35 mm), the result is < 1.7 mm. This is within the acceptable apical deviation suggested in the EAO Consensus of 2012. In a comparison of the angle measurement methods after corrections, there was no significant difference in the guide sleeve angle error observed between group 1 and group 2 (P values < P = .82 and < P = .11; Table 3). Nevertheless, there was a significant difference between the two methods of measurement. The range of measurements following corrections was much smaller, resulting in a statistical significance, but that difference may not be clinically significant. For example, the angular error of the implant results in the apical horizontal error, yet the apical horizontal offset can be determined clinically utilizing the Pythagorean theorem (Fig 10). The amount of the error can be determined by multiplying the length of the implant by the.
tangent of this angle. When tan (3 degrees) is multiplied by 10 mm, the length of the implant, the apical horizontal deviation equals 0.52 mm. A 15-mm implant would then result in the apical horizontal error of 0.78 mm, still less than the 1.7 mm recommended by the 3rd EAO Consensus Conference of 2012, and thus will not be clinically significant.

CONCLUSIONS

The in vitro accuracy of the corrections made with the geometric approach for implant guidance is of similar accuracy to that reported with in vitro studies of stereolithographic surgical guides. The two methods of measurements made with i-CAT and CMM suggest that the accuracy measurement of the angles is similar. The result comparing the two methods is that both methods are statistically similar, and no clinical differences are reported. The case example outlined in this article demonstrated accuracy in implant placement based on a geometric designed surgical guide, supporting its use in treating the edentulous arch when teeth are not present to aid in guiding virtual planning and subsequent guide fabrication.

ACKNOWLEDGMENTS

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

REFERENCES


