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Accuracy of Computer-Aided Dynamic Navigation Compared to Computer-Aided Static Navigation for Dental Implant Placement: An In Vitro Study

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Abstract: Aim: To analyze the accuracy capability of two computer-aided navigation procedures for dental implant placement. Materials and Methods: A total of 40 dental implants were selected, which were randomly distributed into two study groups, namely, group A, consisting of those implants that were placed using a computer-aided static navigation system (n = 20) (guided implant (GI)) and group B, consisting of those implants that were placed using a computer-aided dynamic navigation system (n = 20) (navigation implant (NI)). The placement of the implants from group A was performed using surgical templates that were designed using 3D implant-planning software based on preoperative cone-beam computed tomography (CBCT) and a 3D extraoral surface scan, and the placement of group B implants was planned and performed using the dynamic navigation system. After placing the dental implants, a second CBCT was performed and the degree of accuracy of the planning and placement of the implants was analyzed using therapeutic planning software and Student's t-test. Results: The paired t-test revealed no statistically significant di erences between GI and NI at the coronal (p = 0.6535) and apical (p = 0.9081) levels; however, statistically significant di erences were observed between the angular deviations of GI and NI (p = 0.0272). Conclusion: Both computer-aided static and dynamic navigation procedures allow accurate implant placement.

Keywords: computer-assisted surgery; image-guided surgery; implantology; navigation system; real-time tracking

1. Introduction

Dental implant placement has recently emerged as a predictable treatment option to restore edentulous patients [1]. Nevertheless, some complications are attributed to this technique, including cortical or dental perforations and damage to particular anatomical structures, such as the inferior alveolar nerve or the maxillary sinus, due to implant malpositioning [1,2]. Recently, dental implant placement using image data-based navigation has been introduced into the field of dental surgery in an attempt to improve the accuracy of dental implant placement and avoid potential risks associated with this therapeutic procedure [3]. This surgical approach was developed based on preoperative cone-beam computed tomography (CBCT) scanning and specific 3D implant-planning software, thereby allowing for

accurate implant placement [4]. Generally speaking, there are two types of computer-assisted surgical implant placement system techniques, namely, static navigation and dynamic navigation.

Static navigation systems require the use of surgical templates to guide the drilling process. Dynamic navigation systems recognize and track the position of optical reference markers placed over the patient and surgical instruments by means of a tracking system array. Both navigation techniques have been widely analyzed, demonstrating high accuracy levels for dental implant placement [1,3,5,6]. Static navigation systems have a mean horizontal deviation at the coronal entry point and apical endpoint of 1.2 mm (1.04–1.44 mm) and 1.4 mm (1.28–1.58 mm), respectively, and a mean angular deviation of 3.5 (3.0–3.96) [7]. However, dynamic navigation systems demonstrated lower deviation values at the coronal entry point (0.71 0.40 mm), apical endpoint (1.00 0.49 mm), and angular deviation (2.26 1.62) [8], but these values have not yet been compared.

The aim of this work was to analyze and compare the accuracy of dental implant placement via static and dynamic navigation systems, with a null hypothesis (H0) stating that there would be no di erence between the static and dynamic navigation systems with regard to the accuracy of dental implant placement.

2. Materials and Methods

2.1. Study Design

A randomized controlled experimental trial was conducted in accordance with the principles defined in the International Organization for Standardization (ISO 14801). The study was performed at the Dental Centre of Innovation and Advanced Specialties at Alfonso X El Sabio University (Madrid, Spain) between January and March 2019. This study was authorized by the Ethical Committee of the Faculty of Health Sciences, University Alfonso X el sabio, in December 2018.

2.2. Experimental Procedure

Forty dental implants (BioHorizons, Birmingham, AL, USA) were placed in tooth positions 2.4 and 2.6 (4.6 mm 12 mm, conical wall and internal taper) in twenty standardized polyurethane models of partially edentulous upper jaws (Sawbones Europe AB, Malmo, Sweden) based on one obtained from a real clinical case. The dental implants were randomized (Epidat 4.1, Galicia, Spain) and assigned to one of two study groups: group A, consisting of dental implants that were placed using a computer-aided static navigation system (NemoStudio^{fi}, Nemotec, Madrid, Spain) (n = 20) (guided implant (GI)) and group B, consisting of dental implants that were placed using a computer-aided dynamic navigation system (Navident, ClaroNav, Toronto, Canada) (n = 20) (navigation implant (NI)). The dental implants were first placed in tooth position 2.4, followed by position 2.6, in consideration of a real situation.

The GI jaw models were submitted for a preoperative CBCT scan (WhiteFox, Satelec, Merignac, France) with the following exposure parameters: 105.0 kV peak, 8.0 mA, 7.20 s, and a field of view of 15 mm 13 mm. Afterward, the ten jaw models assigned to the GI study group were submitted for a 3D-extraoral surface scan (EVO, Ceratomic, Protechno, Girona, Spain). Datasets obtained from the digital workflow were uploaded into 3D implant-planning software (NemoStudio^{fi}) to design virtual templates for GI implant placement. The 3D surface scan and CBCT data were matched by aligning the key points present in the partially edentulous upper jaw models. A virtual implant drill was designed with a diameter and length of 4.6 and 12 mm, respectively, as per the measurements of the selected implant (Figure 1A,B). After designing the virtual templates (Figure 1C,D), they were fabricated using the stereolithography technique (ProJet 6000, 3D Systems, Rock Hill, SC, USA) (Figure 1E), except for the 5 mm stainless steel cylinders, which were manually attached to the templates. The templates fit the model and did not need further adjustments.

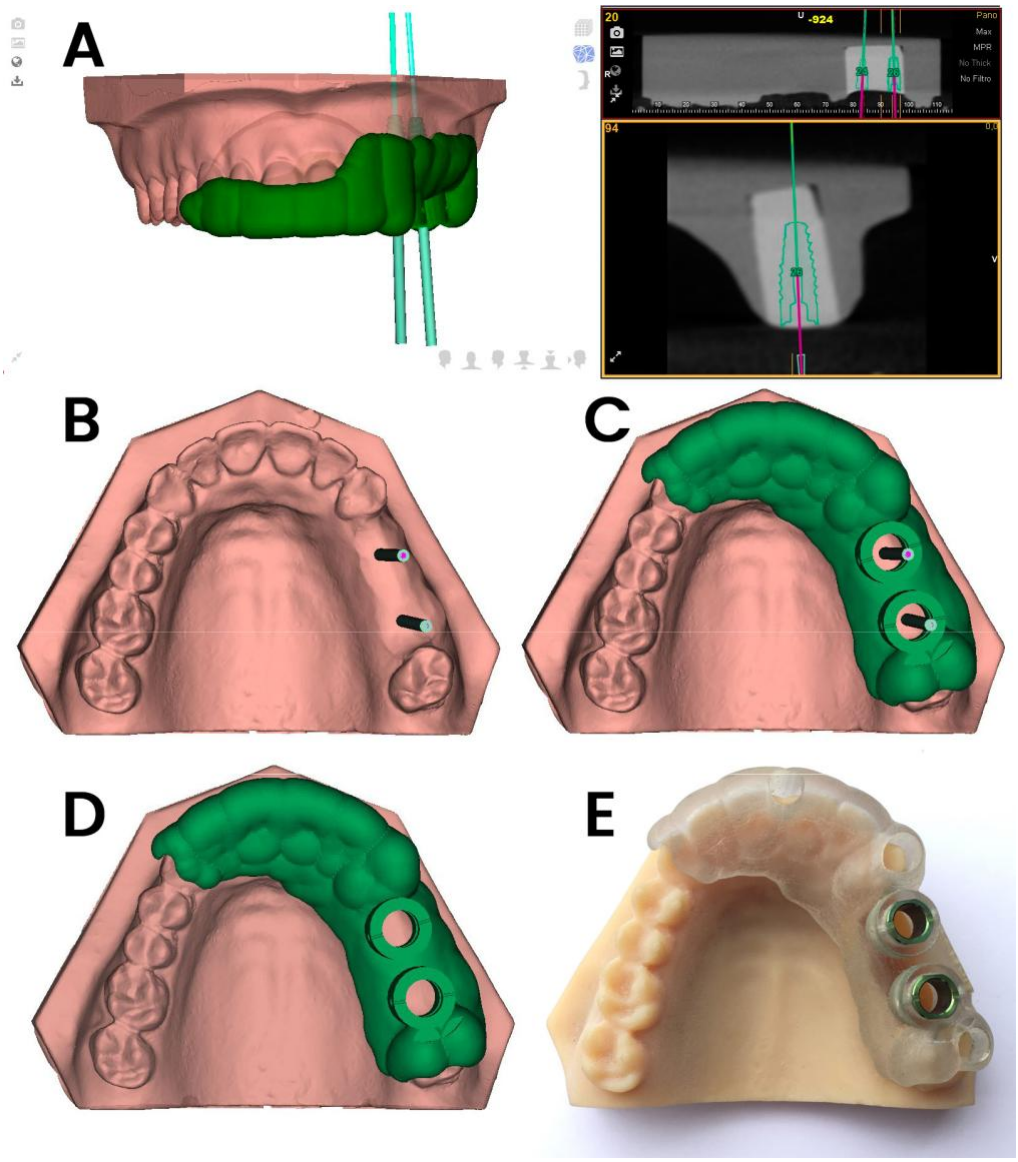

Figure 1. A–C Dental implant planning with the computer-aided static navigation system using a **Figure 1.** (**A**–**C**) Dental implant planning with the computer-aided static navigation system using a cone-beam computed tomography (CBCT) scan (green lines); (**C**,**D**) virtual template design according cone-beam computed tomography (CBCT) scan (green lines); (**C**,**D**) virtual template design according to the planned virtual dental implant placement; (**E**) manufactured stereolithography template fixed to the planned virtual dental implant placement; (**E**) manufactured stereolithography template fixed overover thethe dentaldental surfacesurface ofof thethe teethteeth andand placedplaced overover thethe partiallypartially edentulousedentulous upperupper jawjaw models.models.

The Nl j**aw mode**ls **were subm**itte**d** t**o a preopera**ti**ve CBCT** sca**n pri**o**r** t**o placem**ent **o**ff t**he ther**moplastic te**m**plate ((Navistent, ClaroNav,av, **Toronto**, **ON**, **Canada**) **that includes a radiographic marker** and ananattachedhandlewithwithablackblackandandwhitewhitejaw tjag,w whichtag,whichwasfixedwas overfixedtheoverdentalthe surfacedental surfaceoftheteethof.theCBCTteethdatasets.CBCTweredatasetsimportedwereintoimportedthetreatmentinto-theplanningtreatmentsoftware-planningon msountedftwarelaptopon mountedcomputerlaptopinmobilecomputerunit(Navident,inmobileClaroNav,unit(Navident,Toronto,ClaroNav,Canada) Toronto,simulateCanaddental) implanttosimulateplacementdental implant(Figure 2placementA).Another(Figureblack and2A) .whiteAnotherdrillbltagckwasandattachwhiteddrilltothetaghandpiecewasattached.Bothtoopticalthehandpiecereference. Bothmarkersopticalwerereferencecalibratedmarkersandrecognizedwerecalibratedbytheandopticalrecognizedtriangulationbythe trackingopticaltriangulationsystemcomposedtrackingof systtereoscopicmcomposedmotionof-trackingstereoscopiccamerasmotionwhich-trackingguidedcamerasthedrillingwhichprocessguidedatthetheplanneddrillingangle,processpathway,the

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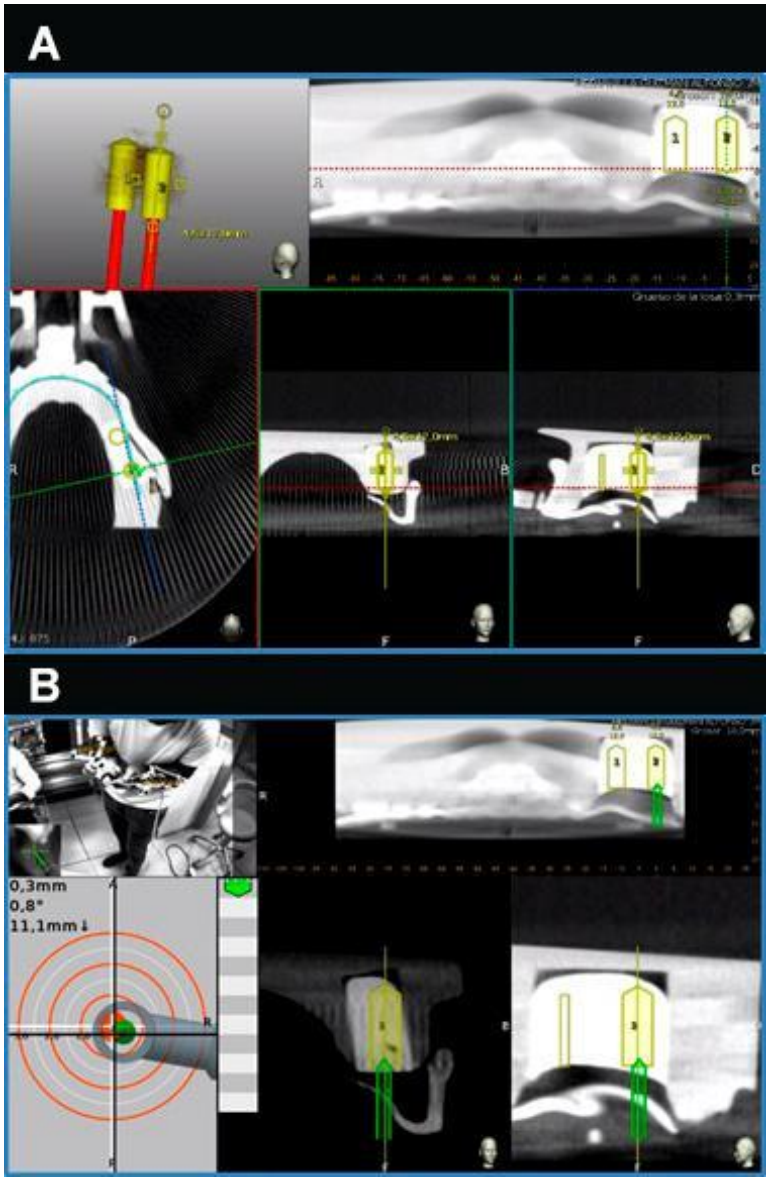

Figure 2. (**A**) Dental implant planning as seen in the treatment-planning software of the computer-**2.** (**A**) Dental implant planning as seen in the treatment-planning software the computer-aided aided dynamic navigation system (yellow cylinders) and (**B**) dental implant placement (green dynamic navigation system (yellow cylinders) and (**B**) dental implant placement (green cylinders) controlled (broken) controlled at all planes and depths. at all planes and depths.

2.3. *Measurement Procedure*

Following the dental implant placement, postoperative CBCT scans were taken. Dental implant planning and postoperative CBCT scans of the study groups were uploaded into 3D implant-planning and postoperative CBCT scans of the study groups were uploaded into 3D implant-software (NemoScan, Nemotec, Madrid, Spain) and matched to analyze apical deviation, which was planning software (NemoScan, Nemotec, Madrid, Spain) and matched to analyze apical deviation,
measured at the apical endpoint; coronal deviation, which was measured at the entry point; and angular which was measured at the apical endpoint; coronal deviation, which was measured at the entry
deviation, which was measured in the center of the cylinder. All noted deviations of all of the implants point; and angular deviation, which was measured the center of the cylinder. All noted deviations
were evaluated and compared in the axial, sagittal, and coronal views (Figure 3A,B) using the same of all of the implants were evaluated and compared in the axial, sagittal, and coronal views (Figure
expertise operator. Results were expressed according to each position.
3A–B) using the same expertise operator. Results were expressed according to each position.

2.4. Statistical Analysis

Statistical analysis of all variables was carried out using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Descriptive statistics were expressed as mean and standard deviation (SD) values for quantitative variables and as absolute numbers and percentages for qualitative variables. Comparative analysis was performed by comparing the mean deviation values between planned and

J. Clinperformed.Med.**2019**implant,8,2123 placements using Student's *t*-test as the variables had a normal distribution. The5of 9 statistical significance was set at $p < 0.05$.

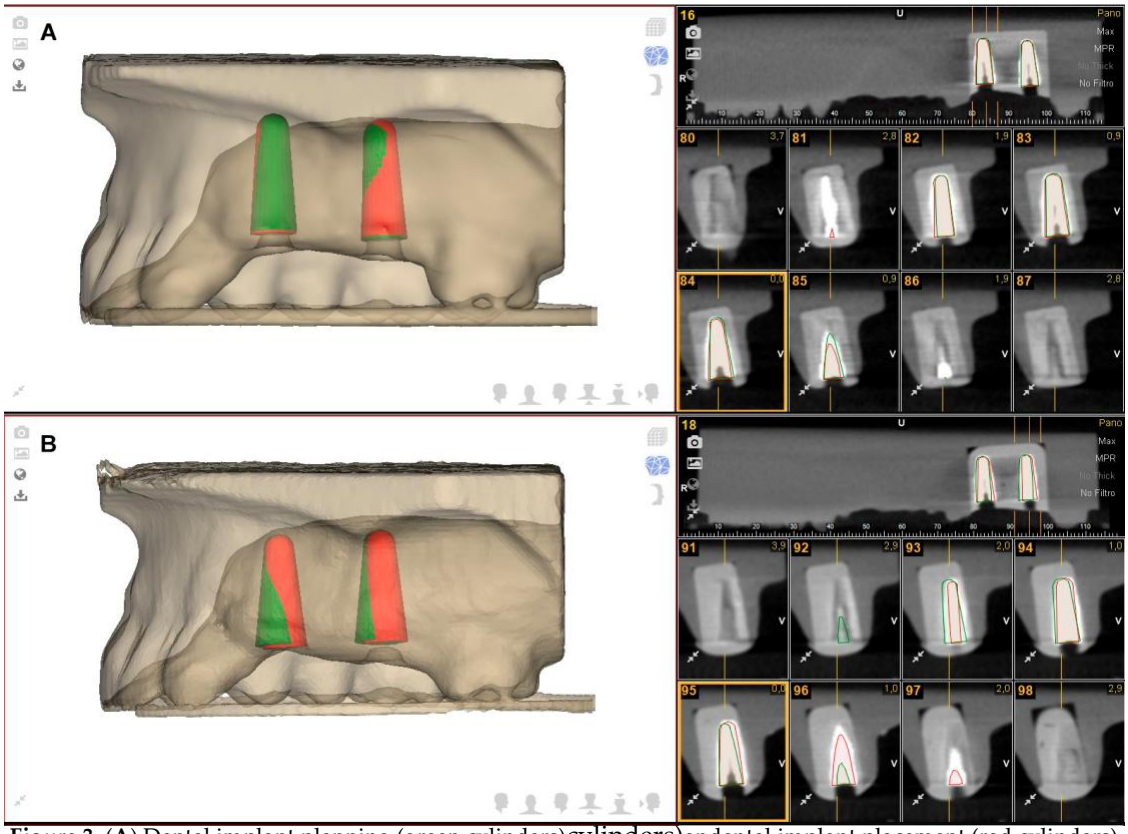

Figure 3. (**A**) Dental implant planning (green cylinders)cylinders)andental implant placement (red cylinders)

Figure 3. (**A**) Dental implant planning (green and dental implant placement (red
using the computer-aided static navigation system and (**B**) the computer-aided dynamic navigation cylinders) using the computer-aided static navigation system and (**B**) the computer-aided dynamic
navigationsystem. system.

2.43. .StatisticalResults Analysis

Statistical analysis of all variables was carried out using SAS 9.4 (SAS Institute Inc., Cary, NC, Table 1 shows the mean and SD values. Mean deviations of 0.78 ± 0.43 mm (min: 0.20 mm; max: USA). Descriptive statistics were expressed as mean and standard deviation (SD) values for quantitative 1.70 mm) and 0.85 ± 0.48 mm (min: 0.30 mm; max: 1.90 mm) were observed at the coronal entry point variables and as absolute numbers and percentages for qualitative variables. Comparative analysis of the GI (Figure 3A) and NI (Figure 3B) study groups, respectively (Figure 4).
was performed by comparing the mean deviation values between planned and performed implant placements**Table**using**1.**Descriptive**Student's**deviation-testasvaluthes variablesattheapicalhad(mm),anormalcoronaldistribution(mm),anda.gularThe (°)statisticallevels(guidedsignificance

was set implantat< 0(GI):.05. static navigation system; navigation implant (NI): dynamic navigation system).

3. Results

	n	Mean	SD	Minimum	Maximum
CORONAL					
GI	20	0.78	0.43	0.20	1.70
NI	20	0.85	0.48	0.30	1.90
APICAL					
GI	20	1.18	0.60	0.20	2.50
NI	20	1.41	1.60	0.60	6.10
ANGULAR					
GI	20	2.95	1.48	0.60	5.20 *
NI	20	4.00	1.60	1.41	6.10

Table 1 shows the meanNI and 20SD values.0.85Mean deviations0.48 of 0.780.300.43 mm (min: 0.201.90 mm; max: 1.70 mm) and 0.85 0.48 mmGI (min:20 0.30 mm;1.20max: 1.90.48mm) were observed0.30 at the coronal2.10entry point of the GI (Figure 3A) and NI (Figure 3B) study groups, respectively (Figure 4).

Table1. Descriptive deviation values at the apical (mm), coronal (mm), and angular ( ) levels (guided implant (GI): static navigation system; navigation implant (NI): dynamic navigation system).

CORONAL	GI	20	0.78	0.43	0.20	1.70
	NI	20	0.85	0.48	0.30	1.90
APICAL	GI	20	1.20	0.48	0.30	2.10
	NI	20	1.18	0.60	0.20	2.50
ANGULAR	GI	20	2.95	1.48	0.60	5.20 *
	NI	20	4.00	1.41	1.60	6.10

Figure 4. Box plots of the coronal deviations observed in the experimental groups. The horizontal lines in each box represent the median values (GI: static navigation system; NI: dynamic navigation

Figuresystem)**4**.. Box plots of the coronal deviations observed in the experimental groups. The horizontal lines

Figure 4. Box plots of the coronal deviations observed in the experimental groups. The horizontal in each box represent the median values (GI: static navigation system; NI: dynamic navigation system).

lines in each box represent the median values (GI: static navigation system; NI: dynamic navigation The paired *t*-test revealed no statistically significant differences between the coronal deviations

Thesystem)paired. t-test revealed no statistically significant di erences between the coronal deviations of GI and NI (p = 0.6535). Mean deviations of 1.20 ± 0.48 mm (min: 0.30 mm; max: 2.10 mm) and 1.18

of GI and NI (p = 0.6535). Mean deviations of 1.20 0.48 mm (min: 0.30 mm; max: 2.10 mm)

± 0.60 mm (min: 0.20 mm; max: 2.50 mm) were observed at the apical endpoint of the GI (Figure 3A) The paired *t*-test revealed no statistically significant differences between the coronal deviations and 1.18 0.60 mm (min: 0.20 mm; max: 2.50 mm) were observed at the apical endpoint of the GI

and NI (Figure 3B) study groups, respectively (Figure 5).

of GI and NI (p = 0.6535). Mean deviations of 1.20 ± 0.48 mm (min: 0.30 mm; max: 2.10 mm) and 1.18 (Figure 3A) and NI (Figure 3B) study groups, respectively (Figure 5).

± 0.60 mm (min: 0.20 mm; max: 2.50 mm) were observed at the apical endpoint of the GI (Figure 3A) and NI (Figure 3B) study groups, respectively (Figure 5).

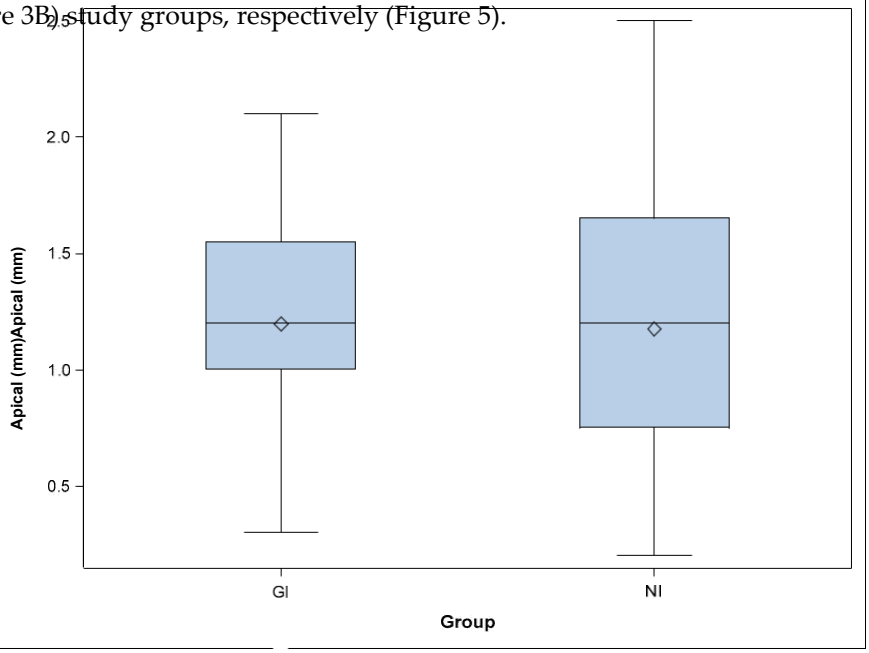

Figure 5. Box plots of the apical deviations observed in the experimental groups. The horizontal lines in each box represent the median values (GI: static navigation system; NI: dynamic navigation system).

Figure 5box.Box**5.** Box plots of the apical deviations observed in the experimental groups. The horizontal lines in**Figure**each representplotsofthemediapicalndeviationsvalues(GI:observedstaticnavigationintheexperisystemental;NI: dynamicgroups. Thenavigathorizontalsystem)lines.

in each box represent the median values (GI: static navigation system; NI: dynamic navigation

The paired t-test revealed no statistically significant di erences between the apical deviations of system).

Figure 5. Box= plots of the apical deviations observed in the experimental groups. The horizontal lines GI and NI (p 0.9081). Mean deviations of 2.95 1.48 (min: 0.60 ; max: 5.20) and 4.00 1.41

(min:The1.60paired:max:*t*- test6.10revealed)were nobservedstatistically in each box represent the median values (GI: static navigation system; NI: dynamic navigation inthesignificantGI(Figuredifferences3A)andbetweenNI(Figuretheapical3B)studydeviationsgroups,of system).

respectivelyGIandNI(p (Figure=0.9081)6.)Mean.The deviationspaired-testof 2revealed.95°±1.48°statistically(min:0.60°;significantmax:5.20°)di anderences4.00° between±1.41°(min:the angular deviations of GI and NI (p = 0.0272).

The paired *t*-test revealed no statistically significant differences between the apical deviations of

GI and NI (p = 0.9081). Mean deviations of 2.95° ± 1.48° (min: 0.60°; max: 5.20°) and 4.00° ± 1.41° (min:

1.60°; max: 6.10°) were observed in the GI (Figure 3A) and NI (Figure 3B) study groups, respectively (Figure 6). The paired *t*-test revealed statistically significant differences between the angular J. Clin. Med. **2019**, 8, 2123 7 of 9 deviations of GI and NI ($p = 0.0272$).

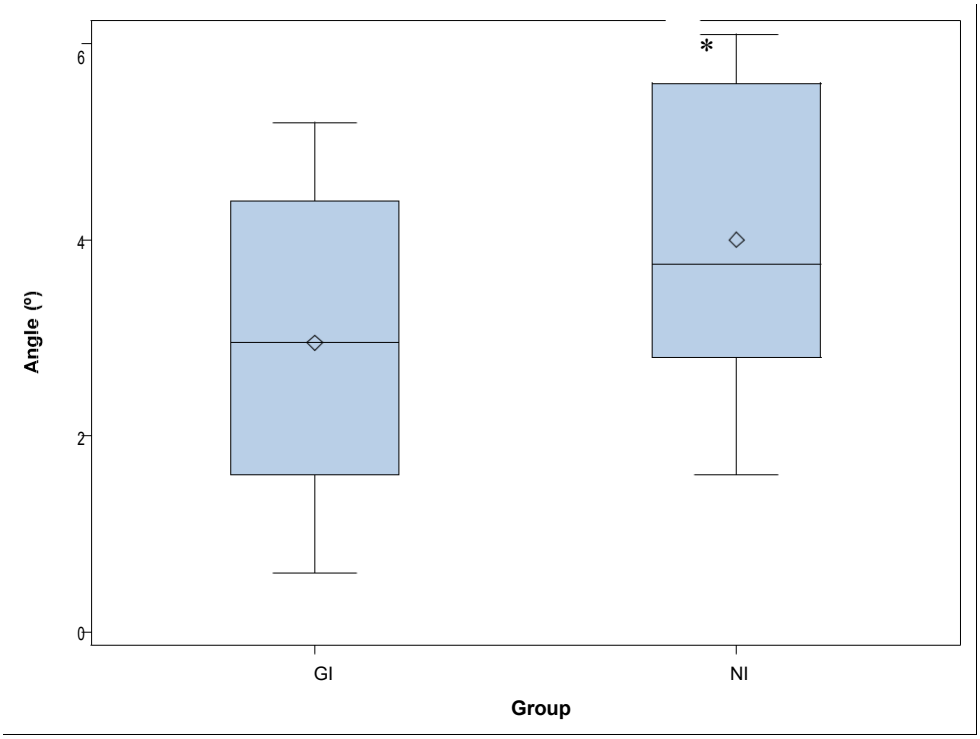

Figure 6. Box plots of the angular deviations observed in the experimental groups. The horizontal lines **Figure 6.** Box plots of the angular deviations observed in the experimental groups. The horizontal in each box represent the median values (GI: static navigation system; NI: dynamic navigation system).
lines in each box represent the median values (GI: static navigation system; NI: dynamic navigation system).

4. Discussion

The results obtained in the present study rejected the null hypothesis (H0) that stated that

4. Discussion

there would be no di erence between computer-aided static and dynamic navigation systems with The results obtained in the present study rejected the null hypothesis (H0) that stated that there regard to the accuracy of dental implant placement. This in vitro study has potential limits related would be no difference between computer-aided static and dynamic navigation systems with regard to the precision and stability of the surgical template due to the use of models, which may have to the accuracy of dental implant placement. This in vitro study has potential limits related to the significantly di ered from what is encountered in a real clinical situation. In recent literature, precision and stability of the surgical template due to the use of models, which may have significantly the accuracy of surgical computer-aided navigation techniques has been widely evaluated and differed from what is encountered in a real clinical situation. In recent literature, the accuracy of compared. Ho mann et al. [9] reported statistically significant di erences in the accuracy of implant surgical computer-aided navigation techniques has been widely evaluated and compared. Hoffmann placement between computer-aided dynamic navigation systems and manual implant placement,
et al. [9] reported statistically significant differences in the accuracy of implant placement between with mean angular deviations of 4.2 1.8 and 11.2 5 , respectively. Although the methods and
computer-aided dynamic navigation systems and manual implant placement, with mean angular selection criteria were slightly di erent from those used in the present study, implant placement using a
deviations of 4.2 ± 1.8° and 11.2 ± 5°, respectively. Although the methods and selection criteria were computer-aided dynamic navigation system o ered a greater degree of accuracy than manual implant
slightly different from those used in the present study, implant placement using a computer-aided placement. Chang-Kai et al. [10] reported similar mean horizontal deviation values at the apical endpoint
dynamic navigation system offered a greater degree of accuracy than manual implant placement. when using a computer-aided dynamic navigation system (1.35 0.55 mm), a computer-aided static Chang-Kai et al. [10] reported similar mean horizontal deviation values at the apical endpoint when navigation system (1.50 0.79 mm), and manual implant placement (2 0.79 mm). Higher angular
using a computer-aided dynamic navigation system (1.35 ± 0.55 mm), a computer-aided static deviation values were reported for the computer-aided dynamic navigation system (4.45 1.97), navigation system (1.50 ± 0.79 mm), and manual implant placement (2 ± 0.79 mm). Higher angular the computer-aided static navigation system (6.02 3.71), and manual implant placement (9.26 3.62).

deviation values were reported for the computer-aided dynamic navigation system (4.45 ± 1.97°), the The accuracy of implant placement with computer-aided navigation systems was shown to be better computer-aided static navigation system (6.02 ± 3.71°), and manual implant placement (9.26 ± 3.62°). than the degree of accuracy during manual procedures, but the angular deviation values were di erent

The accuracy of implant placement with computer-aided navigation systems was shown to be better from the present findings. The learning requirements of computer-aided dynamic navigation systems than the degree of accuracy during manual procedures, but the angular deviation values were might explain the di erences between static and dynamic navigation systems [8]. Computer-aided different from the present findings. The learning requirements of computer-aided dynamic static navigation techniques performed using surgical templates prevent the need for drilling guidance

navigation systems might explain the differences between static and dynamic navigation systems [8]. during surgery [1,3–5]. Therefore, implant placement accuracy depends directly on the design and

Computer-aided static navigation techniques performed using surgical templates prevent the need manufacturing process of the surgical template; if there is an inaccuracy during the fabrication process,

for drilling guidance during surgery [1,3–5]. Therefore, implant placement accuracy depends directly this might lead to intraoperative complications [3]. On the other hand, computer-aided dynamic

on the design and manufacturing process of the surgical template; if there is an inaccuracy during navigation systems allow for a direct view of the surgical field and provide clinicians with the ability

to relocalize the position of an implant, if necessary [9,10]. In addition, these systems are particularly

useful in cases of limited mouth openings or treatments in the posterior region [1,8]. The main disadvantage of computer-aided dynamic navigation systems is the di culty in keeping sight of the dynamic navigation system display during the surgical procedure. However, augmented reality devices could be used to display the virtual image of the computer-aided dynamic navigation system without losing sight of the surgical field [11,12]. Image-guided navigation systems demonstrated comparable accuracy rates regarding control of the depth, position, and angle of implants, which is necessary to avoid intraoperative surgical complications and poor positioning of implants, thereby compromising primary stability and immediate-loading restoration techniques [8,9,12]. In addition, they also avoid the wide excisions often needed to expose the implant platform after the healing period, and enable a minimally invasive transgingival approach to implant placement [1,12]. This is especially helpful in high-risk patients, such as cardiovascular patients taking anticoagulation medications or patients with edentulous, atrophic mandibles [12].

This study shows that computer-aided static and dynamic navigation procedures allow accurate dental implant placement. Nevertheless, further research is needed to determine the influence of the dental implant placement procedure on the accuracy of dental implant positioning and potential clinical complications.

5. Conclusions

In conclusion, within the limitations of this study, the results showed that computer-aided static and dynamic navigation procedures allow accurate implant placement. Nevertheless, it is mandatory to perform a CBCT scan and a 3D surface scan and to plan implant placement using specialized surgical planning software. Clinical trials are necessary to analyze the real behavior of these computer-aided navigation procedures.

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Conflicts of Interest: The authors declare no conflict of interest.

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