

Article

Comparative Evaluation of Two Dynamic Navigation Systems vs. Freehand Approach and Different Operator Skills in Endodontic Microsurgery: A Cadaver Study

Umberto Gibello ^{1,2,†} , Elina Mekhdieva ^{1,*,†} , Mario Alovise ¹ , Luca Cortese ¹, Andrea Cemenasco ¹ , Anna Cassisa ³ , Caterina Chiara Bianchi ¹ , Vittorio Monasterolo ⁴ , Allegra Comba ¹ , Andrea Baldi ¹ , Vittorio Fenoglio ⁵, Elio Berutti ¹  and Damiano Pasqualini ¹ 

- ¹ Department of Surgical Sciences, Dental School, University of Turin, Via Nizza 230, 10126 Turin, Italy; umberto.gibello@unito.it (U.G.); mario.alovise@unito.it (M.A.); luca.cortese@unito.it (L.C.); andrea.cemenasco@unito.it (A.C.); caterinachiara.bianchi@unito.it (C.C.B.); allegra.comba@unito.it (A.C.); andrea.baldi@unito.it (A.B.); elio.berutti@unito.it (E.B.); damiano.pasqualini@unito.it (D.P.)
 - ² Department of Mechanical and Aerospace Engineering—DIMEAS, Polytechnic University of Turin, Corso Duca Degli Abruzzi 24, 10129 Turin, Italy
 - ³ Candiolo Cancer Institute, FPO-IRCCS, Strada Provinciale 142 km 3.95, 10060 Candiolo, Italy; anna.cassisa@ircc.it
 - ⁴ Department of Neurosciences “Rita Levi Montalcini”, University of Turin, via Cherasco 15, 10126 Turin, Italy; vittorio.monasterolo@unito.it
 - ⁵ Department of Surgical Sciences, Dental School, A.O.U. Città della Salute e della Scienza, Corso Bramante 88, 10126 Turin, Italy; fenoglio.vittorio@gmail.com
- * Correspondence: elina.mekhdieva@unito.it
† These authors contributed equally to the work.

Abstract

Background/Objectives: The purpose of the study is to determine and compare the accuracy and efficiency of two dynamic navigation systems (DNS)—Navident (ClaroNav, Canada) and X-Guide (Nobel Biocare, Switzerland)—vs. a free-hand (FH) approach in performing endodontic microsurgery (EMS) on human cadavers. **Methods:** a total of 119 roots of six cadavers were randomly divided into three groups (Navident/X-Guide/FH). The cadavers’ jaws were scanned pre-operatively with computed tomography. The DICOM data were uploaded and digitally managed with software interfaces for registration, calibration, and virtual planning of EMS. Osteotomy was performed under DNS control and using a dental operating microscope (FH control group). Post-operative scans were taken with same settings as preoperative. Accuracy was then determined by comparing pre- and post-scans of coronal and apical linear, angular deviation, angle, length, and depth of apical resection. Efficiency was determined by measuring the procedural time of osteotomy, apicectomy, retro-cavity preparation, the volume of substance, and cortical bone loss, as well as iatrogenic complications. Outcomes were also evaluated in relation to different operators’ skill levels. Descriptive statistics and inferential analyses were conducted using R software (4.2.1). **Results:** DNS demonstrated better efficiency in osteotomy and apicectomy, second only to FH in substance and cortical bone loss. Both DNS approaches had similar accuracy. Experts were faster and more accurate than non-experts in FH, apart from resection angle, length and depth, and retro-cavity preparation time, for which comparison was not statistically significant. The Navident and X-guide groups had similar trends in increasing efficiency and accuracy of EMS. All complications in the FH group were performed by non-experts. The X-guide group demonstrated fewer complications than the Navident group. **Conclusions:** Both DNS appear beneficial for EMS in terms of accuracy and efficacy in comparison with FH, also demonstrating the decreasing gap of



Academic Editor: Bruno Chrcanovic

Received: 22 September 2025

Revised: 15 October 2025

Accepted: 22 October 2025

Published: 24 October 2025

Citation: Gibello, U.; Mekhdieva, E.; Alovise, M.; Cortese, L.; Cemenasco, A.; Cassisa, A.; Bianchi, C.C.; Monasterolo, V.; Comba, A.; Baldi, A.; et al. Comparative Evaluation of Two Dynamic Navigation Systems vs. Freehand Approach and Different Operator Skills in Endodontic Microsurgery: A Cadaver Study. *Appl. Sci.* **2025**, *15*, 11405. <https://doi.org/10.3390/app152111405>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

skill expertise between experts and novice operators. Through convenient use X-guide diminishes the level of iatrogenic complications compared to Navident.

Keywords: endodontic microsurgery; dynamic navigation

1. Introduction

Dynamic navigation systems (DNS) are innovative technologies that facilitate the management of complex endodontic cases (accessing calcified canals, managing complicated anatomy, endodontic retreatment, and microsurgery) [1,2]. Early studies to assess the use of DNS were initially focused on accurate implant placement [3], before expanding to encompass endodontic [4,5] and microsurgical procedures [6,7]. DNS matches spatial positioning technology and preoperative cone-beam computed tomographic (CBCT) imaging, using cameras as an optical triangulation tracking system controlled by computer software [8]. The cameras and motion tracking devices are attached to the dental handpiece and patient, respectively. The DNS device guides drilling at the target position according to a preoperatively planned angle, pathway, and depth of endodontic access cavities, with real-time monitoring [9–12]. As such, DNS enables more accurate and safer endodontic cavity access than conventional freehand (FH) techniques [13]. Furthermore, DNS demonstrates improved usability in posterior regions compared with static guides [14,15], and real-time tracking enables immediate adjustment of the drilling path [16]. These features may help prevent intraoperative complications (such as overextended access cavities, dentin loss, crown and root perforations, missed root canals, the fracture of root canal instruments during canal preparation, or the weakening of the coronal structure), increase efficacy, and reduce procedural time [17–19].

Despite the undeniable practical advantages of DNS, there are associated limitations, with over-dependence on technology being one cause of concern [20]. Most notably, the additional training time required for DNS, alongside complicated instructions, the need for a fundamental learning curve, the additional preoperative time needed for software setup, scanning, virtual designing and tracing, intraoperative calibration and checking time, as well as the difficulty in maintaining the visibility of the system display during clinical procedures, often lead to the adoption of an FH approach instead [21].

However, a qualitative analysis reported benefits of DNS compared with the FH approach, but only in a very limited set of parameters; many associated factors were missed, including detailed accuracy and efficiency variables, as well as iatrogenic damage caused by operators of varying skill levels.

Recently new DNS products have appeared on the market for specialists, with differences in software programs or operating features that could influence the accuracy and efficacy in EMS applications. However, until now there has been no comparative research of different DNS systems versus FH intervention.

Therefore, this study aimed to compare the accuracy and efficacy of two different DNS—Navident and X-Guide—in performing EMS on cadaveric samples as opposed to a free-hand (FH) approach, testing the null hypothesis (H_0) that there would be no differences between DNS groups favoring the FH approach.

2. Materials and Methods

The study was approved by internal review board, IRB (№ 0004315, 23 September 2025). For this study, six cadaver anatomical samples *Cephalus Fresh Defrozen* (Science Care, Coral Springs, FL, USA) were utilized, adhering to the regulations on the use of cadaveric

materials. From these samples, 119 teeth were considered suitable for the finalization of EMS procedures. The number of surgical sites was 115 buccal roots with accessible spots. A subdivision of all the teeth treated has been proposed based on difficulty through a novel scoring system, according to clinical difficulty or target apex [22,23]: high (27), medium (68), and low (24). The web platform <https://www.random.org> (accessed on 4 April 2024) was used to assign the roots to either the Navident, X-Guide, or FH group. All surgical procedures were carried out by the following 4 operators: 2 experienced operators (E/O) with decades of experience, and 2 resident students—non-expert operators (N/E) in the field of microsurgical endodontics. The randomization involved the treatment of 39 sites with the Navident system, 37 sites with the X-Guide system, and 43 with the FH approach, making a total of 119 sites: 56 sites were treated by expert operators (E/O) and 63 sites by non-expert operators (N/E).

The pre-operative CT scans were performed with a GE Revolution 256 CT scanner (General Electric Healthcare, Chicago, IL, USA) with axial scanning (with the voxel size of 0.625 mm, spaced 0.625 mm, 120 kVp, 200 mA, and the rotation time equal to 1 s). DICOM datasets of the CTs were uploaded into corresponding DNS software programs. Virtual surgical planning of the DNS sites—access point, angle, and depth of drilling—was performed, taking into account the need to avoid the neighboring anatomical structures (the maxillary sinus, the floor of the nasal cavity, the mental foramen, and the inferior alveolar nerve). The FH sites were analyzed on the CT slices by the operators; osteotomy, root-end resection, and ultrasonic retro-cavity preparation were performed with a dental operating microscope Extaro 300 (Zeiss, Oberkochen, Germany).

With the aid of dedicated tools, all the CT files were divided into mandibular and maxillary files for each anatomical preparation. Both Navident and similarly X-Guide made it possible to plan the osteotomy and the resection of the apical third perpendicularly to the longitudinal axis of the teeth. In particular, with the second software program, the root was superimposed onto a dental implant, allowing the system to plan a perpendicular osteotomy. Osteotomy was planned virtually with a Bone Mill drill (Nobel Biocare, USA, Yorba Linda, CA, USA) of 5 mm in diameter and 15 mm in length. This allowed the operator to perform both the osteotomy and the apicectomy in the same cutting action.

Before starting surgical procedures, the operators carefully calibrated the Navident and X-Guide systems on the sample jaw. Each DNS site was planned virtually in order to identify and center the target root in 3D planes, perform the osteotomy perpendicular to longitudinal axis of the root, and resect 3 mm of the root apex with a bevel as close as possible to 0°. On the day of surgery, after fixing the anatomical preparation onto a dedicated support, the calibration phase of the X-Guide and Navident systems was performed by experienced operators. Calibration is a delicate phase that is carried out in approximately five minutes and ensures the perfect alignment of the CT data with the patient's anatomical structures, as recorded by the Navident and X-Guide cameras. For the EMS of the maxillary sites treated with the Navident system, a dedicated helmet was used; this tool allowed the Navident stereocamera to follow the operator's movements. For the mandibular sites, a tool called "butterfly" was used, which was stuck to the dental elements with silicone putty (Zhermack Elite, Zhermack SpA, Badia Polesine, Italy), on the opposite side to the sites to be treated. For the calibration of the X-Guide instruments the same procedures were adopted for the maxillary and mandible, with a manufacturer-supplied thermoplastic support adapted to the dental elements of the arch to be treated. Connection to an optical detector read by the X-Guide camera was then made. Handpieces, Expertsurg (Kavo, Biberach, Germany) utilized for the osteotomy by DNS, were fixed to a support that allows its recognition, both from the Navident and X-Guide display systems. Once the recognition system was fixed and activated, registration was made within 20 s for both

systems. The core drills were then calibrated with dedicated support for the Navident and X-Guide systems in 5 s. The Registration phase of the Navident system requires that 6 different points on the teeth surface be selected on the CT, while 3 points must be selected for the X-Guide system. In both cases stitches with metal restorations were avoided to prevent interference in the image. All the selected points were chosen at an equally distributed distance between the selected teeth. A dedicated Tracing Pen was then used for alignment, present in both systems, Navident and X-Guide. This tool allows operators to clearly recognize the dental surfaces previously selected on the CT. Once the cadaver's head was aligned, we proceeded to the verification stage in dynamic navigation in order to confirm a perfect match between the CT images and the clinical reality. At the end of the calibration phase, the stability of supports (the helmet and the butterfly of the Navident system and the support for X-Guide) was checked and confirmed.

Intrasulcular full-thickness flap both at the maxillary and mandibular was elevated to expose the bone site for osteotomy and root end identification. Both operators (E/O and N/E) first proceeded with the tracing to verify on the screen in the guided navigation systems (X-Guide and Navident) the correspondence between the positioning of the bur and the osteotomy axis based on the pre-planning surgical data. The osteotomy was performed from the buccal cortical bone plate to the previously designated end point, including apicectomy. The surgical motor was set at 5000 rpm with irrigation and aspiration by a second operator; osteotomy and apicectomy times were recorded to perform a secondary quantitative parametric assessment.

In the FH group, according to presurgical CT scans measurements from anatomical reference points, osteotomy for root end location and apical resection were performed with a tungsten carbide multiblade Lindemann bur with a speed of 40,000 rpm. EMS procedures were performed with an intraoperative microscope Extaro 300 (Zeiss, Oberkochen, Germany). Once the osteotomy had been carried out, root-end resection was performed with a target bevel range between 0° and 20°. Both in DNS and FH groups a 3 mm retro-cavity preparation was made with ultrasonic Acteon system NEWTRON P5 XS BLED (Acteon Group, Olgiate Alona, Italy) (and ProUltra Surgical tips (Dentsply Sirona, Ballaigues, Switzerland) FH following the long axis of the root canal. Subsequently, post-operative CT scans were taken with the same exposure parameters as the pre-operative CT scans. The acquired DICOM files were imported into Amira software (2024.1) (Thermo Fisher Scientific, Waltham, MA, USA) and superimposed onto the pre-operative ones. Transaxial, coronal, and bone surface tangent images of the registered pre- and post-surgical sites were exported in DICOM format and analyzed with ImageJ software (1.54i) (U. S. National Institute of Health, Bethesda, MA, USA). In order to evaluate virtual and actual consistency, with the aid of Amira software a thresholding of the post-surgical acquisition was performed and a bone surface STL file was created and imported into the planning software for the comparison of virtually planned pre- and post-scans (Figure 1).

The accuracy of each method was evaluated in all the groups by measuring the following outcome parameters: coronal/platform linear deviation (ΔLD_C , mm), apical linear deviation (ΔLD_A , mm), angular deviation (ΔAD , °), volume of substance loss (ΔV , mm³), cortical bone loss (ΔS , mm²); angle (ΔrA , °), length (ΔrL , mm), and depth of the apical resection (ΔrD , mm); preparation of the retro-cavity (consistency with channel axis and depth of the retrograde preparation, mm). The efficiency of each method was evaluated in all groups by measuring the following outcomes: procedural time of the osteotomy (ΔT_OT , s), procedural time of apicectomy (ΔT_AT , s), retrograde preparation time (ΔT_PT , s), complications during apicectomy (irregular bevel, incomplete resection), and others, such as iatrogenic damages (invasion of the maxillary sinus, mandibular canal,

damage to the mental nerve, perforation of the opposite cortex or floor of the nasal cavity) of experienced operators and non-expert operators (E/O, N/E), were also recorded.

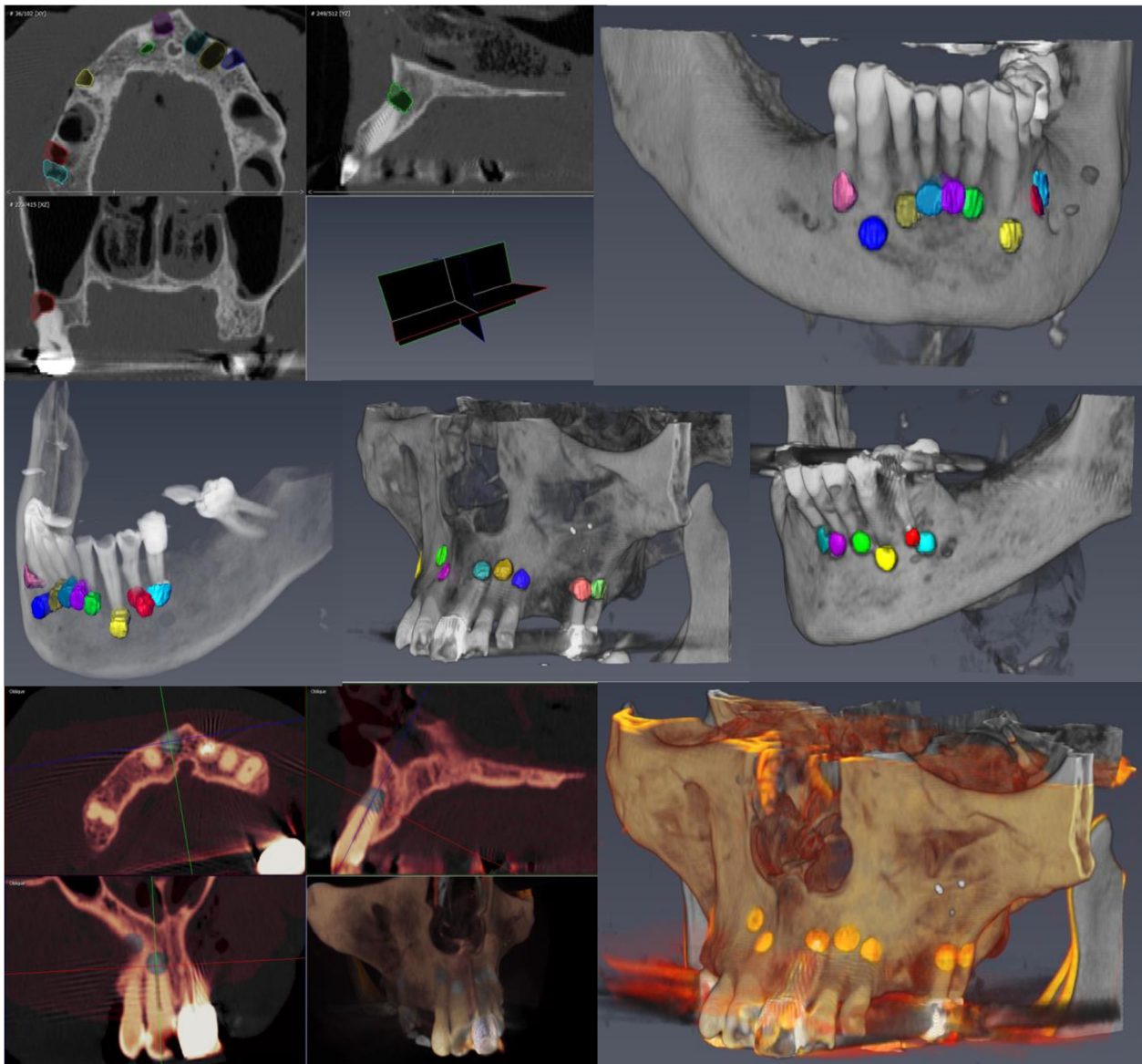


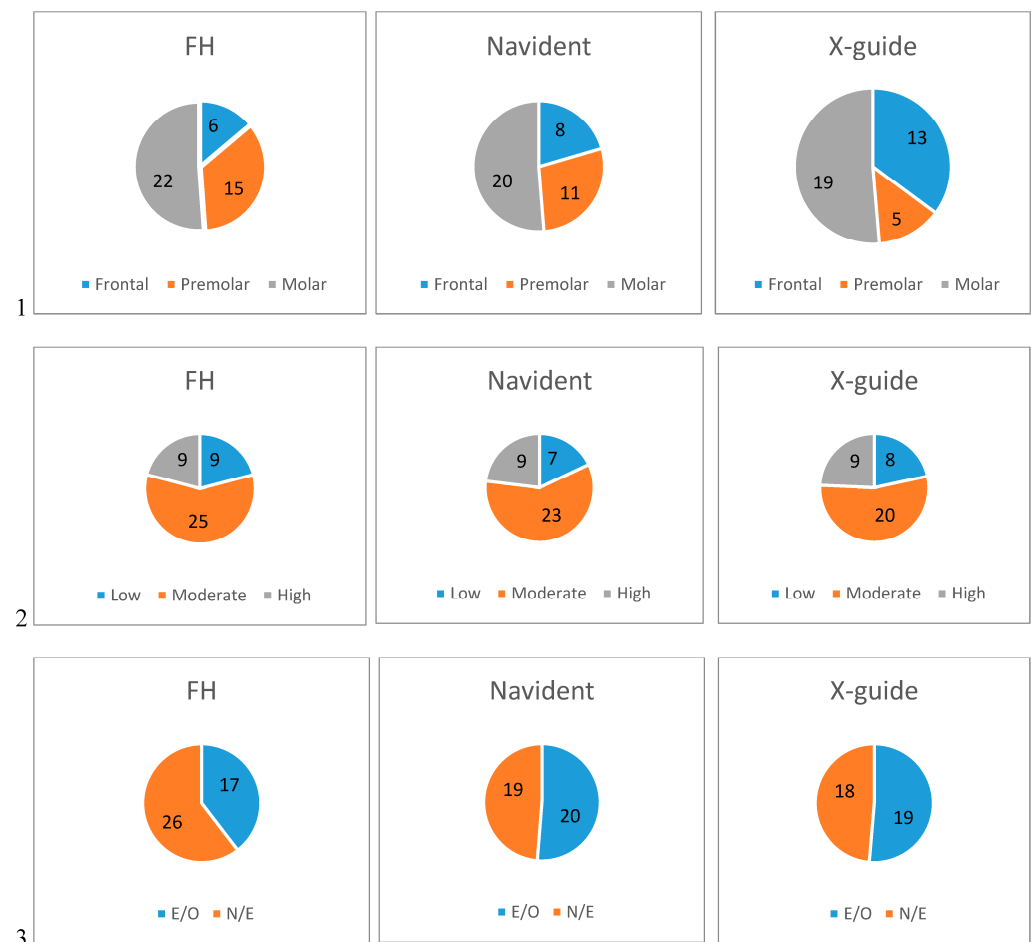
Figure 1. Methodology of DNS in use: comparison of virtually planned pre- and post-scans.

Statistical analyses were performed using the R software (R version 4.2.1, 23 June 2022). Descriptive statistics are expressed as Mean $\pm$ Standard Deviation (SD) for continuous variables. The significance level was set at $p \leq 0.05$. To determine whether the proportions of categorical variables (type of tooth, difficulty, expertise of operator) are homogeneous across different groups, the Chi-square test for homogeneity was used. Intraclass correlation coefficient (ICC) and Fleiss' Kappa were used to assess consistency among the evaluators of continuous and categorical measurements, respectively. The Shapiro–Wilk test was used to analyze the normality of the distribution of the quantitative variables and Student's *t*-test or Mann–Whitney U test were used to estimate statistically significant differences in the variables. One-way and two-way ANOVAs were performed to assess the effects of operative technique (Free Hand, Navident, X-Guide) and operator experience (expert vs. non-expert) on each quantitative outcome. To account for potential confounding factors, including tooth type and jaw (maxilla vs. mandible), and to evaluate the combined influence of technique and operator experience on all outcome variables simultaneously, a

multivariate analysis of variance (MANOVA) was conducted. For prognostic factor analysis, linear regression models were used for continuous variables and generalized linear models (GLMs) for categorical outcomes. Initially, univariate models were applied to each independent variable (type of tooth, case difficulty, expertise of operator) to identify significant factors. A multivariate model was then used to assess the combined effect of these variables on the outcomes, accounting for interactions between independent variables.

3. Results

The 119 treated sites were grouped into three categories as follows: 27 molars, 31 premolars, and 61 frontals. The population was made up of sites divided based on the different difficulty of the sites treated as follows: high (27), medium (68), and low (24) (Figure 2). To obtain reliable results, the previously mentioned outcomes variables were evaluated by three different operators, whose inter-rate agreement was almost perfect, with an average of 0.94 (Fleiss' Kappa) for the qualitative variables and 0.9 (Intraclass Correlation Coefficient, ICC) for the quantitative ones. The sites were grouped homogeneously (according to Chi-square tests, $p > 0.05$) between the treatment groups, both in terms of type of tooth, difficulty, and operator expertise.



1- tooth group; 2- case difficulty; 3- expertise;

FH- free-hand; E/O – expert operators; N/E – non-expert operator

Figure 2. Descriptive statistics of variables.

Table 1A represents descriptive statistics of the quantitative variables evaluated in this study and Mann–Whitney U test p -value, highlighting the difference between the

techniques. The first analysis was conducted to compare FH and DNS approaches. This analysis revealed a significant difference in osteotomy (79.85 ± 46.43 s vs. 43.81 ± 40.62 s, respectively, p adj = 0.0009) and apicectomy time (66.72 ± 33.22 s vs. 42.24 ± 29.18 s, respectively, p adj = 0.0003), suggesting that DNS approach is more efficient in comparison with FH approach. The volume of substance loss was significantly higher in the DNS group in comparison with the FH group (109.90 ± 45.68 mm³ vs. 43.89 ± 27.42 mm³, respectively, p adj = 1.81×10^{-12}), as well as cortical bone loss (124.81 ± 38.82 mm² vs. 65.14 ± 28.55 mm², respectively, p = 8.65×10^{-12}). However, DNS approach showed more precise results in resection angle ($6.54 \pm 6.94^\circ$ vs. $23.08 \pm 14.39^\circ$ FH, p adj = 2.34×10^{-12}), depth of apical resection (1.57 ± 0.61 mm vs. 2.14 ± 0.55 mm FH, p adj = 0.0001).

Table 1. Descriptive statistics of the quantitative variables; (A) FH vs. DNS; (B) Navident vs. X-Guide; (C) ANOVA.

(A)								
	1 *	2 *	3 *	4 *	5 *	6 *	7 *	8 *
	ΔT_{OT} , s	ΔV , mm ³	ΔS , mm ²	ΔT_{AT} , s	ΔrA , °	ΔrL , mm	ΔT_{RT} , s	ΔrD , mm
FH	79.85 ± 46.43	43.89 ± 27.42	65.14 ± 28.55	66.72 ± 33.22	23.08 ± 14.39	2.81 ± 1.51	44.58 ± 21.95	2.14 ± 0.55
DNS	43.81 ± 40.62	109.90 ± 45.68	124.81 ± 38.82	42.24 ± 29.18	6.54 ± 6.94	3.75 ± 1.16	37.04 ± 21.40	1.57 ± 0.61
Effect size	0.3894	−0.6928	−0.6728	0.3686	0.5609	−0.3816	0.2050	0.4134
p adj	0.00092489	1.81×10^{-12}	8.65×10^{-12}	0.00226191	2.34×10^{-8}	0.00043104	0.37522436	0.00012701
(B)								
Navident	18.82 ± 15.53	99.75 ± 44.48	114.06 ± 38.43	30.23 ± 18.61	8.66 ± 8.35	3.89 ± 1.18	40.97 ± 20.47	1.53 ± 0.48
X-Guide	73.33 ± 41.41	121.90 ± 44.80	137.52 ± 35.80	56.42 ± 33.09	4.03 ± 3.47	3.60 ± 1.13	32.07 ± 21.84	1.61 ± 0.75
Effect size	−0.7682	−0.2690	−0.3356	−0.4998	0.3410	0.2284	0.2908	−0.1310
p adj	5.68×10^{-10}	0.17429182	0.03171807	0.00017797	0.0272515	0.42073646	0.13202318	1
(C)								
Anova η^2	0.39787815	0.41722735	0.44019172	0.23845362	0.40038246	0.11848152	0.05477689	0.1866372
Anova p adj	2.74×10^{-10}	1.33×10^{-12}	1.48×10^{-13}	2.20×10^{-5}	6.27×10^{-12}	0.00828	0.6165	0.0001

* FH—free-hand; DNS—dynamic navigation system; 1—Osteotomy time. 2—The volume of substance loss. 3—Cortical bone loss. 4—Apicectomy time. 5—Angle of apical resection. 6—Length of apical resection. 7—Preparation time. 8—Depth of apical resection.

Table 1B shows the comparison of outcomes between both DNS systems, Navident and X-Guide. Navident demonstrated a significantly shorter osteotomy and apicectomy time (18.82 ± 15.53 s and 30.23 ± 18.61 s vs. 73.33 ± 41.41 s and 56.42 ± 33.09 s for X-Guide, respectively). Additionally, Navident demonstrated more accurate results in cortical bone loss (114.06 ± 38.43 mm² and 137.52 ± 35.8 mm² for X-Guide, respectively). A more precise angle of resection was achieved in the X-Guide group ($4.03 \pm 3.47^\circ$ vs. $8.6 \pm 8.35^\circ$ for Navident), while the length and depth of resection were performed with approximately the same level of accuracy.

Table 1C presents the results of the one-way ANOVA comparing the three techniques (FH, Navident, and X-Guide), including partial eta-squared (η^2) as a measure of effect size and p -values. Significant differences among the techniques were found for osteotomy volume, cortical bone area, osteotomy time, apicectomy time, apical resection, resection angle, and resection depth. No significant differences were observed for preparation time.

Table 2 represents the descriptive statistics of the quantitative variables obtained with FH and DNS techniques, considering operator expertise. In general, FH experts demonstrated slightly better results than non-experts across most parameters (lower osteotomy and apicectomy times, smaller bone loss volumes and areas), although these differences were not statistically significant (Table 2A).

Table 2. Descriptive statistics of the quantitative variables (by expertise); (A) FH vs. DNS; (B) Navident vs. X-Guide.

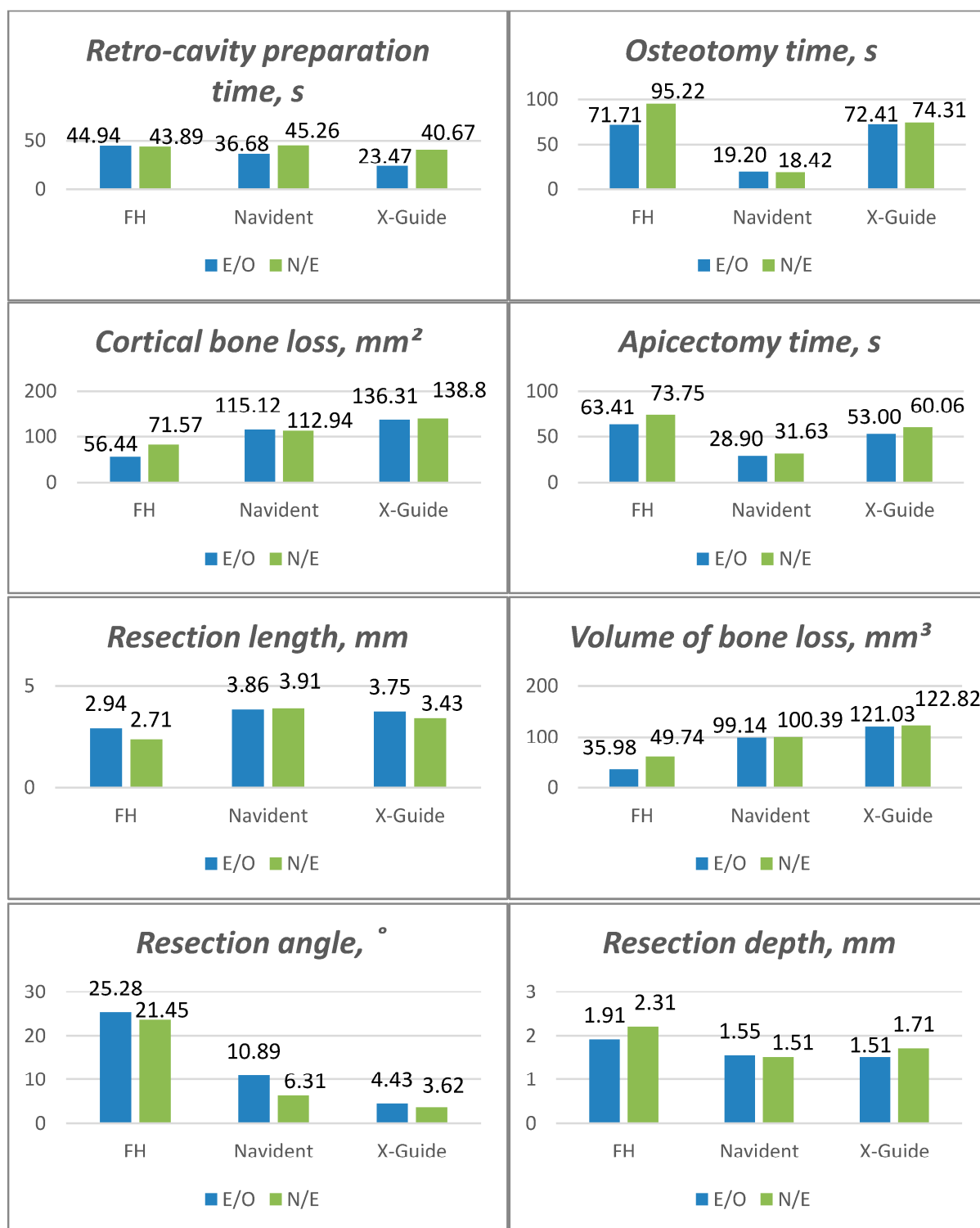
(A)								
	1 *	2 *	3 *	4 *	5 *	6 *	7 *	8 *
	$\Delta T_{OT,s}$	$\Delta V, mm^3$	$\Delta S, mm^2$	$\Delta T_{AT,s}$	$\Delta rA, ^\circ$	$\Delta rL, m$	$\Delta T_{RT,s}$	$\Delta rD, mm$
FH E/O	71.71 $\pm$ 47.13	35.98 $\pm$ 15.95	56.44 $\pm$ 15.17	63.41 $\pm$ 32.99	25.28 $\pm$ 15.03	2.94 $\pm$ 1.70	44.94 $\pm$ 26.58	1.91 $\pm$ 0.37
FH N/E	95.22 $\pm$ 43.46	49.74 $\pm$ 32.61	71.57 $\pm$ 34.29	73.75 $\pm$ 34.83	21.45 $\pm$ 14.00	2.71 $\pm$ 1.38	43.89 $\pm$ 9.53	2.31 $\pm$ 0.60
Effect size	−0.3066358	−0.1881871	−0.1903413	−0.163303	0.26517528	−0.0086519	−0.1111374	−0.7874489
<i>p</i> adj	1	1	1	1	1	1	1	1
DNS E/O	43.65 $\pm$ 43.18	109.19 $\pm$ 47.36	124.86 $\pm$ 39.31	39.97 $\pm$ 29.30	7.92 $\pm$ 8.55	3.81 $\pm$ 1.21	30.85 $\pm$ 16.68	1.54 $\pm$ 0.60
DNS N/E	43.97 $\pm$ 38.36	110.64 $\pm$ 44.53	124.76 $\pm$ 38.87	44.63 $\pm$ 29.30	5.08 $\pm$ 4.34	3.69 $\pm$ 1.12	43.24 $\pm$ 23.92	1.60 $\pm$ 0.62
Effect size	−0.018598	−0.0305391	0.00252726	−0.116927	0.15402317	0.10220327	−0.2954299	−0.10435
<i>p</i> adj	1	1	1	1	1	1	0.4750	1
(B)								
	1 *	2 *	3 *	4 *	5 *	6 *	7 *	8 *
	$\Delta T_{OT,s}$	$\Delta V, mm^3$	$\Delta S, mm^2$	$\Delta T_{AT,s}$	$\Delta rA, ^\circ$	$\Delta rL, m$	$\Delta T_{RT,s}$	$\Delta rD, mm$
Navident E/O	19.20 $\pm$ 15.27	99.14 $\pm$ 48.80	115.12 $\pm$ 40.51	28.90 $\pm$ 19.47	10.89 $\pm$ 10.23	3.86 $\pm$ 1.32	36.68 $\pm$ 18.50	1.55 $\pm$ 0.42
Navident N/E	18.42 $\pm$ 16.21	100.39 $\pm$ 40.77	112.94 $\pm$ 37.19	31.63 $\pm$ 18.09	6.31 $\pm$ 5.02	3.91 $\pm$ 1.06	45.26 $\pm$ 21.91	1.51 $\pm$ 0.54
Effect size	0.03381433	0.04274252	0.00224961	−0.0946994	0.22271103	0.12823405	−0.4240738	−0.0292464
<i>p</i> adj	1	1	1	1	1	1	1	1
X-Guide E/O	72.41 $\pm$ 47.87	121.03 $\pm$ 44.08	136.31 $\pm$ 35.63	53.00 $\pm$ 33.87	4.43 $\pm$ 4.01	3.75 $\pm$ 1.10	23.47 $\pm$ 10.52	1.51 $\pm$ 0.80
X-Guide N/E	74.31 $\pm$ 34.81	122.82 $\pm$ 46.99	138.80 $\pm$ 37.11	60.06 $\pm$ 32.94	3.62 $\pm$ 2.85	3.43 $\pm$ 1.17	40.67 $\pm$ 26.81	1.71 $\pm$ 0.70
Effect size	0.09730019	−0.0394919	−0.0683741	−0.1600075	−0.0031353	−0.0846532	−0.4284846	−0.258503
<i>p</i> adj	1	1	1	1	1	1	0.6058	1

* FH—free-hand; DNS—dynamic navigation system; 1—Osteotomy time. 2—The volume of substance loss. 3—Cortical bone loss. 4—Apicectomy time. 5—Angle of apical resection. 6—Length of apical resection. 7—Preparation time. 8—Depth of apical resection.

Table 2B shows the comparison between expert (E/O) and non-expert (N/E) operators for the Navident and X-Guide navigation systems that identifies no differences in accuracy and efficiency between E/O and N/E of two DNS, but the results are not statistically significant ($p > 0.5$).

Figure 3 represents these results graphically according to groups based on their expertise.

To account for potential confounding by jaw (maxilla/mandible) and tooth type, a multivariate analysis of variance (MANOVA) was performed including technique, expertise, jaw, and tooth type as factors. After Bonferroni correction for multiple testing, surgical technique remained the only factor with a significant effect on the main quantitative outcomes. The influence of operator expertise was limited, showing only minor, non-significant trends in a few timing and angular parameters ($p > 0.05$ after correction). Jaw location demonstrated modest effects on apical resection and retro-cavity preparation time (raw $p < 0.05$, not significant after correction), whereas tooth type was associated only with resection angle (adjusted $p = 0.048$). No significant interactions were detected between technique and operator. Overall, these findings confirm that differences in accuracy and efficiency were primarily attributable to the surgical technique, rather than operator experience or anatomical factors. Detailed F- and p -values (raw and Bonferroni-adjusted) for each variable are reported in Table 3.



FH- free-hand; E/O – expert operators; N/E – non-expert operator

Figure 3. Efficiency variables (by expertise).

Table 3. MANOVA test results.

Effect	1 *	2 *	3 *	4 *	5 *	6 *	7 *	8 *
	$\Delta T_{OT}, s$	$\Delta V, mm^3$	$\Delta S, mm^2$	$\Delta T_{AT}, s$	$\Delta rA, ^\circ$	$\Delta rL, m$	$\Delta T_{RT}, s$	$\Delta rD, mm$
Technique (F Manova)	29.575	37.557	43.653	12.807	33.495	4.452	2.781	3.484
Technique (p Manova)	7.56×10^{-9}	8.92×10^{-11}	4.01×10^{-12}	0.00056	8.05×10^{-10}	0.5812	1	1
Expertise (F Manova)	0.657	0.384	0.269	0.827	6.042	0.123	4.375	0.193
Expertise (p Manova)	1	1	1	1	0.6409	1	1	1
Tooth (F Manova)	0.081	1.753	1.582	0.119	7.306	2.594	0.827	0.035
Tooth (p adj Manova)	1	1	1	1	0.0475	1	1	1
Jaw (F Manova)	3.888	2.878	2.781	0.433	4.716	8.526	4.547	0.093
Jaw (p adj Manova)	1	1	1	1	1	0.1797	1	1
Technique: Expertise (F Manova)	1.939	0.335	0.273	0.284	0.970	0.653	1.175	0.404
Technique: Expertise (p Manova)	1	1	1	1	1	1	1	1

* 1—Osteotomy time. 2—The volume of substance loss. 3—Cortical bone loss. 4—Apicectomy time. 5—Angle of apical resection. 6—Length of apical resection. 7—Preparation time. 8—Depth of apical resection.

A descriptive analysis of iatrogenic damage, with three observers in agreement, revealed seven perforations of the maxillary sinus membrane at different sites: three of them carried out using Navident (1.5, 1.7, 2.7), two using the FH approach (N/E) (1.5, 1.7), and two using X-Guide (E/O, N/E) (1.6, 1.6). Furthermore, two perforations were at the level of the lingual mandibular cortex at sites 3.1 and 4.1 (one with Navident, another one with the FH approach, N/E), and damage at the level of the palatine cortex at site 1.1 carried out with Navident. No damage was detected to the floor of nasal cavity, the inferior alveolar nerve, and at the level of mental nerve emergence. An incomplete partial resection with related complications that prevented proper apical preparation occurred in twenty-five cases, of which twelve occurred in the FH technique, nine with Navident, and four with X-Guide.

For the detection of prognostic factors that influence the outcomes, linear regression was performed for each variable. The tooth group was found to be a significant factor in the resection angle ($p = 0.0124$), with multi-rooted teeth having a smaller angle than single-rooted teeth. Additionally, more difficult cases correlated significantly with increased bone loss volume ($p = 0.003$), cortical bone loss ($p = 0.005$), resection depth ($p = 0.0239$), and complications ($p = 0.0386$). The DNS approach increased the volume of substance bone loss and cortical bone loss ($p = 8.17 \times 10^{-12}$ and $p = 1.33 \times 10^{-12}$), while the FH increased osteotomy, apicectomy time, and resection angle ($p = 0.0003$; $p = 0.0005$; $p = 4.06 \times 10^{-10}$, respectively).

The study additionally involved a direct comparison of the results obtained using X-Guide and Navident in relation to pre-defined “target” values. A paired-sample Student’s *t*-test identified significant differences ($p < 0.05$) between the two techniques for the resection angle and resection length (Table 4). Further comparison of the mean errors for each technique against a theoretical zero-mean vector indicated that, for most variables, both systems exhibited errors significantly different from zero ($p < 0.05$). However, no significant difference from zero was observed for apical deviation (both DNS techniques) and for resection length (using the X-Guide system).

Table 4. (A) Descriptive statistics of accuracy variables; (B) Comparison against a theoretical zero-mean vector.

(A)						
	1 *	2 *	3 *	4 *	5 *	6 *
	$\Delta LD_C, \text{ mm}$	$\Delta LD_A, \text{ mm}$	$\Delta AD, ^\circ (0^\circ \text{ axis})$	$\Delta AD, ^\circ (90^\circ \text{ axis})$	$\Delta rA, ^\circ$	$\Delta rL, \text{ mm}$
Navident	1.25 ± 0.35	-0.04 ± 0.98	5.48 ± 4.83	4.97 ± 4.71	10.27 ± 6.25	2.48 ± 1.40
X-guide	1.21 ± 0.61	-0.02 ± 1.43	4.17 ± 3.94	7.72 ± 8.97	5.03 ± 7.65	0.50 ± 1.74
p-value	>0.05	>0.05	>0.05	>0.05	<0.05	<0.05
(B)						
	1 *	2 *	3 *	4 *	5 *	6 *
	$\Delta LD_C, \text{ mm}$	$\Delta LD_A, \text{ mm}$	$\Delta AD, ^\circ (0^\circ \text{ axis})$	$\Delta AD, ^\circ (90^\circ \text{ axis})$	$\Delta rA, ^\circ$	$\Delta rL, \text{ mm}$
Navident vs. X-guide, p-value	0.79169	0.9505	0.2403	0.2304	0.0013	1.75×10^{-5}
Navident vs. 0, p-value	4.59×10^{-14}	0.8419	4.29×10^{-5}	4.30×10^{-5}	7.59×10^{-8}	2.13×10^{-8}
X-guide vs. 0, p-value	6.46×10^{-13}	0.9326	1.23×10^{-6}	8.33×10^{-7}	0.00015	0.1114

* 1—coronal/platform linear deviation; 2—apical linear deviation; 3—angular deviation (0° axis); 4—angular deviation (90° axis); 5—resection angle; 6—resection length.

4. Discussion

The study represents multiple variables measured to assess the accuracy and efficiency of the FH approach and two DNS (Navident and X-Guide) approaches simultaneously. These DNS were chosen for comparison as two most widely used systems available and were also compared to FH as the control group. The parameters of efficiency are expanded on by measuring the procedural time of three steps—osteotomy, apicectomy, and preparation of retro-cavity (FH). Bone volume was also separately assessed in detail for substance bone loss and cortical bone loss. EMS precision was evaluated by four deviation variables (coronal deviation, apical deviation, 0° , and 90° axis angular deviation) and three resection parameters (angle, length, and depth). This detailed and multivariable approach has not been observed in current studies. Operator expertise, iatrogenic complications, and associated factors were explored. Although several studies were identified, our study design and wide variables range differ in an advantageous way. In our study, procedural time was the primary variable used to assess the efficacy of the approach. This was measured and presented in the following two distinct stages: osteotomy time and apicectomy time. Our findings, demonstrating that DNS is effective at reducing procedural time across all stages, are consistent with results from other studies. However, they evaluated only the total duration of the procedure, not the individual stages. Martinho et al. [21] reported that the time required for osteotomy and root-end resection using an FH approach was double that of the DNS approach, regardless of operator experience. We, on the other hand, underlined that experts were faster in the Navident and X-guide groups. It was not possible to compare with studies of combined procedural stages, such as with Tang et al. [20], who did not detail how the beginning and end step of each procedure corresponded to recorded time. Thus, differences in procedural time may be influenced by inter-study variation in the measurement of time parameters.

Regarding bone loss, our results are in direct contrast to other published studies. These studies generally concluded that the DNS approach leads to significantly less substance loss than the FH approach [24]. We demonstrated substance bone loss as well as cortical bone loss (a factor not taken into account in existing works and therefore comparisons cannot be made). Jain et al. [13] conversely reported significantly less mean substance loss with the DNS approach compared with the FH approach. Additionally, Connert et al. [19] favored the DNS approach in this respect, this being further supported by Janabi et al. [1]

and Tang et al. [20]. We could theoretically explain it by the possible probable difference in the diameter of the trephine bur used.

The superior accuracy of DNS approach compared to FH approach, particularly in the measurement of coronal linear and apical deviations, is fully consistent with studies by Gambarini et al. [25], who determined that the DNS approach was significantly more precise with less angular and linear deviation, and with Janabi et al. [1], who reported a similar statistically significant result. Subsequently, Martinho et al. [21] also confirmed significantly higher accuracy using DNS vs. FH approaches and verified that expert operators achieved higher accuracy with the DNS systems compared with novice operators. Finally, Dianat et al. [26] also observed significantly less deviation and angular deflection with DNS approaches vs. FH approaches. According to Tang et al. [20], the DNS approach significantly reduced the gap in these parameters, as compared with FH groups, regardless of the operator experience. In our study several accuracy variables—angular deviation of the 90° axis, resection angle, length, and depth—were estimated and results also demonstrated more accuracy in DNS group.

In summary, DNS approaches are associated with minimized potential risk of iatrogenic complications. A key difference from the FH approach is that, while the new DNS system significantly reduces the overall number of complications, FH does not prevent experts to perform some iatrogenic perforations and incomplete resections, although significantly less frequent than non-expert operators, concluding that operator skill level is not the only variable affecting outcomes and, furthermore, that these devices are user-friendly for novice operators and reduce gap between experts and non-experts. In our study, the X-guide system demonstrated significantly fewer cases of iatrogenic complications than the Navident system. As expected, the descriptive analyses of six quantitative variables revealed that both the Navident and X-Guide navigation systems demonstrated deviations from the planned trajectory. All these aspects and the lightly better performance may suggest that digital planning, the calibration phase, and the surgical phase seem to be more user-friendly with the X Guide technology than Navident. All these above mentioned allow rejecting of the set null hypothesis (H_0) of absence of differences between DNS groups favoring the FH approach. To our knowledge, there is no other study comparing two different DNS systems operated by clinicians of different levels of expertise. The existent studies [6,7] have only compared other procedural variables apart from iatrogenic issues. There is potentially a need for more studies to precisely determine the skill and experience level required to achieve optimal results using DNS systems.

This study has some limitations. First, performing procedures on cadavers is different from operating on real patients in terms of physiology and blood supply, something which definitely might affect clear visibility in some of EMS steps. A further limitation of our study is that the cadavers' fixed state and immobility is likely to have contributed to the high precision of the scanning and navigation processes. We believe that working with real patients could significantly alter these results. Therefore, large-scale, multi-center clinical studies are necessary to clarify these concerns.

5. Conclusions

Based on the findings of this study, both the Navident and X-Guide DNS systems appear beneficial for microsurgical endodontics, demonstrating superior accuracy and efficacy compared to the FH approach and decreasing gap of skill expertise between experts and novice operators. Through convenient use X-guide group demonstrated fewer iatrogenic complications compared to Navident group, although it had similar trends in increasing efficiency and accuracy of EMS. To further validate these findings, high-quality studies with a larger number of participants are needed. Future research should also

include operators with diverse skill levels and incorporate both cadaver and patient models to assess the systems' performance more comprehensively.

Author Contributions: Conceptualization: V.M., A.C. (Andrea Cemenasco), V.F. and A.C. (Anna Cassisa); Methodology: U.G. and L.C.; Software: C.C.B., A.C. (Anna Cassisa) and L.C.; Validation: A.B., A.C. (Andrea Cemenasco) and M.A.; Formal analysis: A.C. (Anna Cassisa) and A.C. (Andrea Cemenasco); Investigation: C.C.B. and L.C.; Resources: A.C. (Allegra Comba); Data curation: U.G.; Writing—original draft: E.M.; Writing—review and editing: D.P. and E.M.; Visualization: C.C.B.; Supervision: D.P. and E.B.; Project administration: D.P., E.B., U.G. and E.M. contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The protocol was reviewed and approved by Institutional Review Board, IRB, of University of Turin (N° 0004315, 23 September 2025).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data available on request due to ethical and legal reasons.

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

References

1. Janabi, A.; Tordik, P.A.; Griffin, I.L.; Price, J.B.; Chand, P.; Martinho, F.C. Accuracy and efficiency of 3-dimensional dynamic navigation system for removal of fiber post from root canal-treated teeth. *J. Endod.* **2021**, *47*, 1453–1460. [\[CrossRef\]](#) [\[PubMed\]](#)
2. Pujol, M.L.; Vidal, C.; Mercadé, M.; Munoz, M.; Ortolani-Seltenerich, S. Guided endodontics for managing severely calcified canals. *J. Endod.* **2021**, *47*, 315–321. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Panchal, N.; Mahmood, L.; Retana, A.; Emery, R. Dynamic navigation for dental implant surgery. *Oral Maxillofac. Surg. Clin. N. Am.* **2019**, *31*, 539–547. [\[CrossRef\]](#)
4. Dianat, O.; Nosrat, A.; Tordik, P.A.; Romberg, E.; Price, J.B.; Mostoufi, B. Accuracy and efficiency of a dynamic navigation system for locating calcified canals. *J. Endod.* **2020**, *46*, 1719–1725. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Connert, T.; Weiger, R.; Krastl, G. Present status and future directions—Guided endodontics. *Int. Endod. J.* **2022**, *55*, 995–1002. [\[CrossRef\]](#)
6. Aldahmash, S.A.; Price, J.B.; Mostoufi, B.M.; Dianat, O.; Tordik, P.A.; Martinho, F.C. Real-time 3d image-guided navigation system in endodontic microsurgery: A cadaver study. *J. Endod.* **2022**, *48*, 922–929. [\[CrossRef\]](#)
7. Wang, Z.; Chen, C.; Qin, L.; Li, F.; Chen, Y.; Meng, L. Accuracy and efficiency of endodontic microsurgery assisted by dynamic navigation based on two different registration methods: An in vitro study. *J. Endod.* **2023**, *49*, 1199–1206. [\[CrossRef\]](#)
8. Buchgreitz, J.; Buchgreitz, M.; Bjørndal, L. Guided root canal preparation using cone beam computed tomography and optical surface scans—An observational study of pulp space obliteration and drill path depth in 50 patients. *Int. Endod. J.* **2019**, *52*, 559–568. [\[CrossRef\]](#)
9. Jain, S.D.; Carrico, C.K.; Bermanis, I. 3-Dimensional accuracy of dynamic navigation technology in locating calcified canals. *J. Endod.* **2020**, *46*, 839–845. [\[CrossRef\]](#)
10. Simon, J.C.; Kwok, J.W.; Vinculado, F.; Fried, D. Computer-controlled CO₂ laser ablation system for cone-beam computed tomography and digital image guided endodontic access: A pilot study. *J. Endod.* **2021**, *47*, 1445–1452. [\[CrossRef\]](#)
11. Leontiev, W.; Connert, T.; Weiger, R.; Krastl, G.; Magni, E. Dynamic navigation in endodontics: Guided access cavity preparation by means of a miniaturized navigation system. *J. Vis. Exp.* **2022**, *183*, e63687. [\[CrossRef\]](#)
12. Liu, S.; Zhao, Y.; Wang, X.; Wang, Z. In vitro evaluation of positioning accuracy of trephine bur at different depths by dynamic navigation. *J. Peking Univ. (Med. Ed.)* **2022**, *54*, 146–152. [\[CrossRef\]](#)
13. Jain, S.D.; Saunders, M.W.; Carrico, C.K.; Jadhav, A.; Deeb, J.G.; Myers, G. Dynamically navigated versus freehand access cavity preparation: A comparative study on substance loss using simulated calcified canals. *J. Endod.* **2020**, *46*, 1745–1751. [\[CrossRef\]](#)
14. Connert, T.; Zehnder, M.S.; Amato, M.; Weiger, R.; Kuhl, S.; Krastl, G. Microguided endodontics: A method to achieve minimally invasive access cavity preparation and root canal location in mandibular incisors using a novel computer-guided technique. *Int. Endod. J.* **2018**, *51*, 247–255. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Zubizarreta-Macho, A.; Munoz, A.P.; Deglow, E.R.; Agustin-Panadero, R.; Alvarez, J.M. Accuracy of computer-aided dynamic navigation compared to computer-aided static procedure for endodontic access cavities: An in vitro study. *J. Clin. Med.* **2020**, *9*, 29. [\[CrossRef\]](#) [\[PubMed\]](#)

16. Chong, B.S.; Dhesi, M.; Makdissi, J. Computer-aided dynamic navigation: A novel method for guided endodontics. *Quintessence Int.* **2019**, *50*, 196–202. [[CrossRef](#)] [[PubMed](#)]
17. Connert, T.; Krug, R.; Eggmann, F.; Weiger, R.; Kuhl, S.; Krastl, G. Guided endodontics versus conventional access cavity preparation: A comparative study on substance loss using 3-dimensional-printed teeth. *J. Endod.* **2019**, *45*, 327–331. [[CrossRef](#)]
18. Torres, A.; Boelen, G.-J.; Lambrechts, P.; Pedano, M.S.; Jacobs, R. Dynamic navigation: A laboratory study on the accuracy and potential use of guided root canal treatment. *Int. Endod. J.* **2021**, *54*, 1659–1667. [[CrossRef](#)]
19. Connert, T.; Leontiev, W.; Dagassan-Berndt, D.; Krug, R.; Krastl, G. Real-time guided endodontics with a miniaturized dynamic navigation system versus conventional freehand endodontic access cavity preparation: Substance loss and procedure time. *J. Endod.* **2021**, *10*, 1651–1656. [[CrossRef](#)]
20. Tang, W.; Jiang, H. Comparison of static and dynamic navigation in root end resection performed by experienced and inexperienced operators: An in vitro study. *J. Endod.* **2022**, *49*, 294–300. [[CrossRef](#)]
21. Martinho, F.C.; Aldahmash, S.; Cahill, T.; Price, J.B.; Griffin, I.L.; Tordik, P.A. Comparison of the accuracy and efficiency of a 3D dynamic navigation system for osteotomy and root-end resection performed by novice and experienced endodontists. *J. Endod.* **2022**, *48*, 1327–1333. [[CrossRef](#)]
22. von Arx, T.; Janner, S.F.M.; Jensen, S.S.; Bornstein, M.M. The resection angle in apical surgery: A CBCT assessment. *Clin. Oral Investig.* **2016**, *20*, 2075–2082. [[CrossRef](#)]
23. Azim, A.A.; Albanyan, H.; Azim, K.A.; Piasecki, L. The Buffalo study: Outcome and associated predictors in endodontic microsurgery—A cohort study. *Int. Endod. J.* **2021**, *54*, 301–318. [[CrossRef](#)]
24. Mekhdieva, E.; Del Fabbro, M.; Alovisei, M.; Scotti, N.; Comba, A.; Berutti, E.; Pasquallini, D. Dynamic Navigation System vs. Free-Hand Approach in Microsurgical and Non-Surgical Endodontics: A Systematic Review and Meta-Analysis of Experimental Studies. *J. Clin. Med.* **2023**, *12*, 5845. [[CrossRef](#)] [[PubMed](#)]
25. Gambarini, G.; Galli, M.; Stefanelli, L.V.; Di Nardo, D.; Morese, A.; Seracchiani, M.; De Angelis, F.; Di Carlo, S.; Testarelli, L. Endodontic microsurgery using dynamic navigation system: A case report. *J. Endod.* **2019**, *45*, 1397–1402.e6. [[CrossRef](#)] [[PubMed](#)]
26. Dianat, O.; Nosrat, A.; Mostoufi, B.; Price, J.B.; Gupta, S.; Martinho, F.C. Accuracy and efficiency of guided root-end resection using a dynamic navigation system: A human cadaver study. *Int. Endod. J.* **2021**, *54*, 793–801. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.