

# Accuracy of Dynamic Navigation Systems in Implant Surgery and Prosthetic Outcomes

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## ABSTRACT:

### Background:

Precise implant positioning is essential for achieving favorable prosthetic outcomes, minimizing complications, and ensuring long-term implant success. Dynamic navigation has emerged as an advanced computer-assisted technology that enables real-time guidance during implant placement and may improve surgical accuracy compared with the conventional freehand technique.

### Aim:

To compare the accuracy of dynamic navigation-guided implant placement with the conventional freehand technique and to evaluate their influence on prosthetic outcomes, complications, marginal bone loss, implant survival, and patient satisfaction.

### Materials and Methods:

This comparative clinical study included 40 patients requiring implant-supported rehabilitation, with a total of 58 dental implants. Twenty-nine implants were placed using a dynamic navigation system, while 29 implants were inserted using the conventional freehand technique. Implant placement accuracy was assessed by measuring coronal, apical, angular, and depth deviations using postoperative CBCT analysis. Primary implant stability was evaluated using the Implant Stability Quotient (ISQ). Prosthetic outcomes included prosthetic alignment, emergence profile, requirement for angled abutments, prosthetic complications, and marginal bone loss. Surgical complications included implant survival, patient satisfaction, and correlations between implant placement deviations and prosthetic outcomes were also evaluated. Statistical analysis was performed using independent samples t-tests, Chi-square/Fisher's exact tests, and Pearson's correlation analysis, with statistical significance set at  $p < 0.05$ .

### Results:

The Dynamic Navigation Group demonstrated significantly

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lower coronal ( $0.72 \pm 0.24$  vs.  $1.31 \pm 0.43$  mm), apical ( $0.91 \pm 0.31$  vs.  $1.67 \pm 0.52$  mm), angular ( $2.18 \pm 0.86^\circ$  vs.  $5.14 \pm 1.72^\circ$ ), and depth deviations ( $0.64 \pm 0.27$  vs.  $1.08 \pm 0.39$  mm) than the Conventional Freehand Group (all  $p < 0.001$ ). Ideal prosthetic alignment ( $89.7\%$  vs.  $62.1\%$ ;  $p = 0.014$ ), ideal emergence profile ( $86.2\%$  vs.  $65.5\%$ ;  $p = 0.035$ ), and reduced requirement for angled abutments ( $6.9\%$  vs.  $27.6\%$ ;  $p = 0.037$ ) were significantly better with dynamic navigation. Marginal bone loss was significantly lower in the Dynamic Navigation Group ( $0.48 \pm 0.21$  mm vs.  $0.64 \pm 0.32$  mm;  $p = 0.029$ ), while overall patient satisfaction was significantly higher across all evaluated domains ( $p < 0.05$ ). Implant survival was excellent in both groups ( $100.0\%$  vs.  $96.6\%$ ;  $p = 1.000$ ), and no significant differences were observed in primary implant stability, surgical complications, or prosthetic complications. Significant negative correlations were observed between implant placement deviations and prosthetic outcome scores, with angular deviation demonstrating the strongest correlation ( $r = -0.614$ ,  $p < 0.001$ ).

### Conclusion:

Dynamic navigation-guided implant placement provides significantly greater positional accuracy than the conventional freehand technique, resulting in improved prosthetic alignment, emergence profile, marginal bone preservation, and patient satisfaction. Although implant survival, primary stability, and complication rates were comparable between the techniques, the enhanced precision achieved with dynamic navigation supports its use as a reliable approach for predictable prosthetically driven implant placement.

**Keywords:** CBCT, Computer-assisted surgery, Dental implant, Dynamic navigation, Implant placement accuracy, Prosthetic outcomes, Patient satisfaction

### Introduction

Dental implant therapy has become one of the most predictable treatment modalities for replacing missing teeth, demonstrating high long-term survival rates and favorable functional and esthetic outcomes. The success of implant-supported rehabilitation depends not only on osseointegration but also on accurate three-dimensional implant positioning, which directly influences prosthetic emergence profile, occlusal loading, peri-implant tissue health, and long-term maintenance. Prosthetically driven implant placement has therefore become the fundamental principle of modern implant dentistry, emphasizing precise control of implant angulation, depth, and mesiodistal and

buccolingual positioning to achieve optimal restorative outcomes [1].

Conventional freehand implant placement relies heavily on the clinician's anatomical knowledge and surgical experience. Although experienced clinicians can achieve acceptable outcomes, freehand surgery is associated with greater deviations from the planned implant position, particularly in anatomically challenging regions or when multiple implants are placed. These inaccuracies may compromise esthetics, increase the risk of damage to adjacent anatomical structures such as the inferior alveolar nerve or maxillary sinus, and complicate prosthetic rehabilitation by necessitating angled abutments or customized restorations [2].

To improve surgical precision, computer-assisted implant surgery has evolved into two principal approaches: static computer-guided surgery and dynamic navigation systems. Static guidance utilizes stereolithographic surgical guides fabricated from virtual implant planning. While static guides improve accuracy compared with freehand surgery, they possess several limitations, including restricted irrigation, limited intraoperative flexibility, inaccuracies caused by guide instability, and inability to modify implant positioning once surgery has commenced [3].

Dynamic navigation systems represent a significant technological advancement by providing real-time computer-assisted guidance throughout implant osteotomy and implant placement. These systems combine cone-beam computed tomography (CBCT) imaging, virtual implant planning software, optical tracking cameras, and calibration instruments to continuously monitor the position of the surgical handpiece relative to the patient's anatomy. This technology allows clinicians to visualize drill trajectory, angulation, and depth on a monitor during surgery while permitting intraoperative modifications whenever necessary [4].

Numerous clinical and experimental investigations have demonstrated that dynamic navigation significantly improves implant placement accuracy compared with conventional freehand techniques. Reported deviations at the coronal platform, implant apex, and angular orientation generally remain within clinically acceptable limits, approaching the precision achieved with static surgical guides. Furthermore, dynamic navigation offers the additional advantage of maintaining direct visualization of the surgical field without requiring bulky surgical templates, making it particularly useful in patients with limited mouth opening, posterior regions, or complex anatomical situations [5, 6].

The increased precision afforded by dynamic navigation has important implications for prosthetic rehabilitation. Accurate implant positioning facilitates ideal prosthetic emergence

profiles, minimizes the need for corrective prosthetic components, improves passive fit of implant-supported restorations, enhances esthetic outcomes, and contributes to favorable distribution of occlusal forces. Accurate implant placement also reduces the likelihood of biological and mechanical complications, thereby improving long-term implant survival and patient satisfaction [7].

Despite these advantages, successful implementation of dynamic navigation requires careful patient registration, precise system calibration, and operator training. The technology involves a learning curve, and surgical accuracy may be influenced by clinician experience, tracking stability, calibration errors, and patient movement during the procedure. Consequently, continuous evaluation of navigation accuracy under clinical conditions remains essential for validating its effectiveness and identifying factors influencing performance [8].

Recent systematic reviews and meta-analyses have consistently concluded that dynamic navigation provides significantly greater accuracy than freehand implant placement while demonstrating accuracy comparable to static computer-guided surgery. Moreover, the flexibility to adjust implant positioning during surgery without compromising precision makes dynamic navigation an attractive option for prosthetically driven implant rehabilitation, particularly in anatomically demanding clinical scenarios [9].

Given the growing adoption of digital workflows in implant dentistry, understanding the influence of dynamic navigation on both surgical accuracy and prosthetic outcomes is increasingly important. Evaluating these parameters provides valuable evidence regarding the clinical effectiveness of navigation technology and its contribution to predictable implant-supported rehabilitation. Therefore, the present study aims to assess the accuracy of dynamic navigation systems in implant surgery and to evaluate their impact on prosthetic outcomes, thereby contributing to evidence-

based decision-making in digital implant dentistry [10].

## Materials & Methods

### Study Design

The present study was designed as a prospective clinical observational study to evaluate the accuracy of dynamic navigation systems in dental implant surgery and their influence on prosthetic outcomes. The study was conducted at a single tertiary care centre. All participants provided written informed consent before enrollment.

### Study Population

The study included 40 patients and a total of 58 dental implants, with 29 implants in the Dynamic Navigation Group and 29 implants in the Conventional Freehand Group. Patients were recruited consecutively between January 2025 and December 2025.

### Inclusion Criteria

- Patients aged 18–70 years
- Partially edentulous patients requiring one or more dental implants
- Adequate bone volume for implant placement with or without minor guided bone regeneration
- Patients willing to undergo CBCT examination and follow-up visits
- Good oral hygiene and adequate periodontal health
- Patients willing to complete prosthetic rehabilitation and attend follow-up visits for clinical and radiographic evaluation

### Exclusion Criteria

- Uncontrolled systemic diseases (ASA III or higher)
- Pregnancy or lactation
- Heavy smokers (>10 cigarettes/day)
- Active periodontal disease or untreated oral infection
- Patients requiring major bone augmentation procedures
- Previous radiotherapy involving the head and neck region

- Inability to comply with follow-up protocol

### Preoperative Planning

Each patient underwent a comprehensive clinical examination followed by CBCT and intraoral digital scanning. Digital Imaging and Communications in Medicine (DICOM) files obtained from CBCT were merged with Standard Tessellation Language (STL) files generated from the intraoral scanner using dedicated implant planning software.

Virtual implant planning was performed using a prosthetically driven approach. Implant diameter, length, angulation, depth, and mesiodistal positioning were planned according to the final prosthetic restoration while maintaining safe distances from adjacent teeth and vital anatomical structures such as the inferior alveolar nerve, mental foramen, maxillary sinus, and nasal floor.

### Dynamic Navigation Procedure

Implant placement in the conventional group was performed using conventional freehand surgical techniques based on preoperative CBCT planning without real-time navigation guidance. Before surgery; calibration of the surgical handpiece and navigation instruments was completed according to the manufacturer's recommendations. Registration of the patient's jaw was performed using fiducial markers or trace registration, depending on the navigation protocol. Real-time tracking enabled continuous visualization of drill trajectory, implant depth, and angulation throughout osteotomy preparation and implant placement. All surgeries were performed by the same experienced implant surgeon to minimize operator-related variability.

### Prosthetic Rehabilitation

Following an appropriate healing period of 3–4 months, implant-supported prostheses were fabricated according to standard prosthodontic protocols. Prosthetic evaluation included assessment of:

- Prosthetic alignment
- Emergence profile

- Requirement for angled abutments
- Prosthetic complications (screw loosening, prosthetic modification, occlusal adjustment)
- Marginal bone loss
- Implant survival
- Patient satisfaction

### Accuracy Assessment

Postoperative CBCT scans were obtained immediately after implant placement. Planned and actual implant positions were superimposed using implant evaluation software.

The following parameters were measured:

- Coronal deviation (mm)
- Apical deviation (mm)
- Angular deviation (degrees)
- Depth deviation (mm)

### Outcome Measures

#### Primary Outcome

- Accuracy of implant placement measured by coronal, apical, angular, and depth deviations.

#### Secondary Outcomes

- Primary implant stability
- Prosthetic alignment
- Emergence profile
- Requirement for angled abutments
- Surgical complications
- Prosthetic complications
- Marginal bone loss
- Implant survival
- Patient satisfaction
- Correlation between implant placement deviations and overall prosthetic outcome score

### Statistical Analysis

Data will be entered into a Microsoft Excel spreadsheet and analyzed using an appropriate statistical software package such as IBM SPSS Statistics, version 26.0 or later. Data will be checked for completeness, accuracy, and consistency before statistical analysis.

Continuous quantitative variables, including coronal deviation, apical deviation, angular deviation, depth deviation, primary implant stability measured using the Implant Stability Quotient (ISQ), marginal bone loss, and patient satisfaction scores, will be summarized using mean and standard deviation (Mean  $\pm$  SD). Categorical variables, including age group, gender, anatomical implant location, prosthetic alignment, emergence profile, requirement for angled abutments, surgical complications, prosthetic complications, and implant survival, will be expressed as frequency and percentage [n (%)].

The normality of continuous variables will be assessed using the Shapiro–Wilk test, supplemented by visual inspection of histograms and Q–Q plots where appropriate. For normally distributed continuous variables, comparisons between the Dynamic Navigation and Conventional Freehand groups will be performed using the independent samples Student's t-test. Accordingly, this test will be used to compare coronal deviation, apical deviation, angular deviation, depth deviation, primary implant stability, marginal bone loss, and patient satisfaction scores between the two groups. If the assumptions of normality are not satisfied, the Mann–Whitney U test will be used as the corresponding non-parametric alternative.

Categorical variables will be compared between the two study groups using the Chi-square test of independence. When expected cell frequencies are less than 5, particularly for outcomes with sparse observations such as major prosthetic corrections, compromised emergence profile, implant failure, surgical complications, or prosthetic complications, the Fisher's exact test or Fisher–Freeman–Halton exact test will be applied as appropriate.

The association between implant placement accuracy and overall prosthetic outcomes will be assessed using Pearson's correlation coefficient ( $r$ ) when both variables satisfy the assumptions of approximate normality and linearity. The relationships of coronal deviation, apical deviation, angular deviation, and depth deviation

with the overall prosthetic outcome score will be separately evaluated. If these assumptions are not satisfied, Spearman's rank correlation coefficient ( $\rho$ ) will be used instead. The strength and direction of correlations will be interpreted according to the magnitude and sign of the correlation coefficient.

Where appropriate, multiple linear regression analysis may additionally be performed to identify independent predictors of the overall prosthetic outcome score. Potential predictor variables may include coronal deviation, apical deviation, angular deviation, depth deviation, implant location, and other clinically relevant covariates. Regression assumptions, including linearity, normality and homoscedasticity of residuals, independence of errors, and multicollinearity, will be assessed before interpretation of the final model.

All statistical tests will be two-tailed, and a  $p$  value  $< 0.05$  will be considered statistically significant. A  $p$  value  $< 0.001$  will be reported as highly statistically significant where applicable. Results will be presented using appropriate tables and graphical representations.

## Results

The present study evaluated 40 patients requiring implant-supported rehabilitation, with a total of 58 dental implants. For comparative presentation, 29 implants were included in the Dynamic Navigation Group and 29 implants in the Conventional Freehand Group. The following tables summarize demographic characteristics, implant placement accuracy,

prosthetic outcomes, complications, marginal bone loss, implant survival, patient satisfaction, and correlations between placement accuracy and prosthetic outcomes.

Table 1 & Figure 1 present the distribution of study participants according to demographic characteristics. The findings showed that the majority of participants were aged 31–45 years (37.5%), followed by those aged 46–60 years (30.0%), 18–30 years (22.5%), and 61–70 years (10.0%). In the Dynamic Navigation Group, 25.0% of participants were aged 18–30 years, 35.0% were aged 31–45 years, 30.0% were aged 46–60 years, and 10.0% were aged 61–70 years. Similarly, in the Conventional Freehand Group, the corresponding proportions were 20.0%, 40.0%, 30.0%, and 10.0%, respectively. The difference in age distribution between the two study groups was not statistically significant ( $p = 0.916$ ), indicating that the groups were comparable with respect to age.

Regarding gender distribution, males constituted the majority of the overall study population, accounting for 57.5%, while females constituted 42.5%. In the Dynamic Navigation Group, 55.0% of participants were male and 45.0% were female, whereas in the Conventional Freehand Group, 60.0% were male and 40.0% were female. The difference in gender distribution between the two groups was not statistically significant ( $p = 0.749$ ). Overall, the absence of significant differences in age and gender distribution indicates that the Dynamic Navigation and Conventional Freehand groups were demographically comparable at baseline.

**Table 1: Distribution of Study Participants According to Demographic Characteristics**

| Demographic characteristic | Dynamic Navigation Group n (%) | Conventional Freehand Group n (%) | Total n (%) | P value |
|----------------------------|--------------------------------|-----------------------------------|-------------|---------|
| Age group (years)          |                                |                                   |             |         |
| 18–30                      | 5 (25.0)                       | 4 (20.0)                          | 9 (22.5)    | 0.916   |
| 31–45                      | 7 (35.0)                       | 8 (40.0)                          | 15 (37.5)   |         |
| 46–60                      | 6 (30.0)                       | 6 (30.0)                          | 12 (30.0)   |         |
| 61–70                      | 2 (10.0)                       | 2 (10.0)                          | 4 (10.0)    |         |
| Gender                     |                                |                                   |             |         |
| Male                       | 11 (55.0)                      | 12 (60.0)                         | 23 (57.5)   | 0.749   |
| Female                     | 9 (45.0)                       | 8 (40.0)                          | 17 (42.5)   |         |

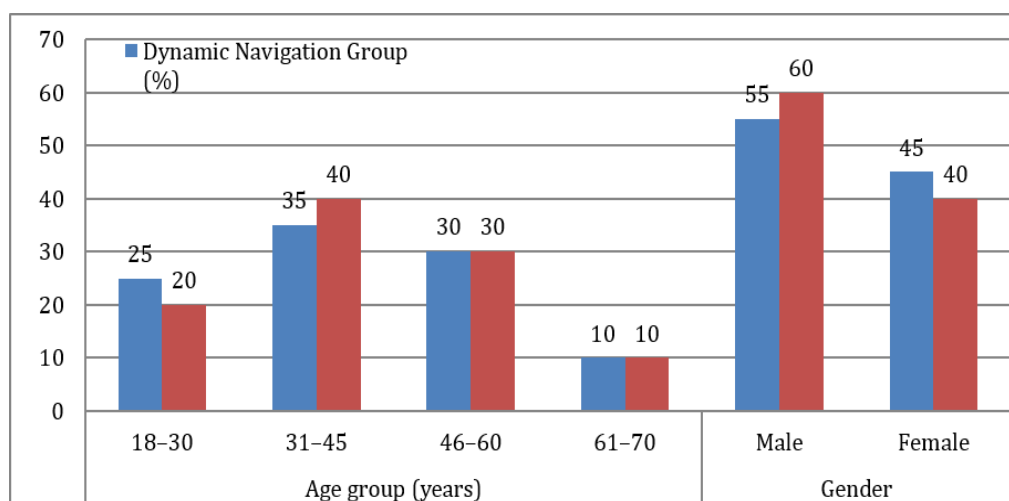


**Figure 1: Distribution of study participants according to age group and gender in the Dynamic Navigation and Conventional Freehand groups at baseline**

Table 2 & Figure 2 present the distribution of dental implants according to anatomical location. The findings demonstrated a comparable distribution pattern between the Dynamic Navigation and Conventional Freehand groups. Overall, the mandibular posterior region was the most common implant location, accounting for 18 implants (31.0%), followed by the maxillary posterior region with 17 implants (29.3%), the maxillary anterior region with 13 implants (22.4%), and the mandibular anterior region with 10 implants (17.2%). In the Dynamic Navigation Group, 7 implants (24.1%) were placed in the maxillary anterior region, 8 (27.6%) in the maxillary posterior region, 5 (17.2%) in the mandibular anterior region, and 9 (31.0%) in the mandibular posterior region.

Similarly, in the Conventional Freehand Group, 6 implants (20.7%) were placed in the maxillary anterior region, 9 (31.0%) in the maxillary posterior region, 5 (17.2%) in the mandibular anterior region, and 9 (31.0%) in the mandibular posterior region. The difference in the distribution of implants according to anatomical location between the two study groups was not statistically significant ( $p = 0.968$ ). This indicates that the Dynamic Navigation and Conventional Freehand groups were comparable with respect to implant location, thereby minimizing the potential influence of anatomical site distribution on the comparative assessment of implant placement outcomes.

**Table 2: Distribution of Dental Implants According to Anatomical Location**

| Implant location     | Dynamic Navigation Group n (%) | Conventional Freehand Group n (%) | Total n (%) | P value |
|----------------------|--------------------------------|-----------------------------------|-------------|---------|
| Maxillary anterior   | 7 (24.1)                       | 6 (20.7)                          | 13 (22.4)   | 0.968   |
| Maxillary posterior  | 8 (27.6)                       | 9 (31.0)                          | 17 (29.3)   |         |
| Mandibular anterior  | 5 (17.2)                       | 5 (17.2)                          | 10 (17.2)   |         |
| Mandibular posterior | 9 (31.0)                       | 9 (31.0)                          | 18 (31.0)   |         |
| Total                | 29 (100.0)                     | 29 (100.0)                        | 58 (100.0)  |         |

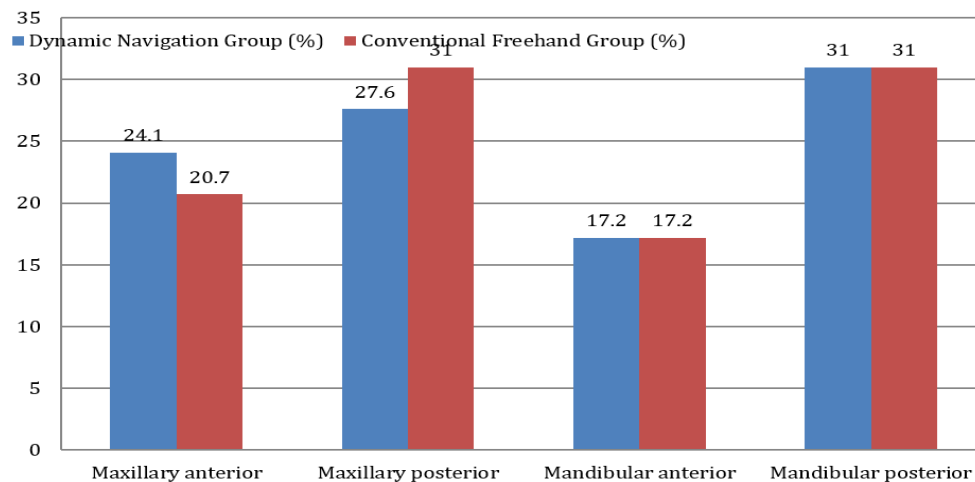


**Figure 2: Age and gender distribution of participants in the Dynamic Navigation and Conventional Freehand groups**

Table 3 & Figure 3 present the comparison of coronal deviation between the study groups. The findings demonstrated that the Dynamic Navigation Group had a significantly lower mean coronal deviation ( $0.72 \pm 0.24$  mm) than the Conventional Freehand Group ( $1.31 \pm 0.43$  mm). The mean difference between the two groups was 0.59 mm.

Statistical analysis revealed a t value of 6.62, and the difference in coronal deviation between the

two groups was highly statistically significant ( $p < 0.001$ ). These findings indicate that the Dynamic Navigation technique achieved significantly greater accuracy at the coronal entry point compared with the Conventional Freehand technique, with substantially less deviation from the virtually planned implant position.

**Table 3: Comparison of Coronal Deviation Between the Study Groups**

| Group                 | N  | Mean deviation (mm) | SD   | Mean difference | t value | P value |
|-----------------------|----|---------------------|------|-----------------|---------|---------|
| Dynamic Navigation    | 29 | 0.72                | 0.24 | 0.59            | 6.62    | <0.001  |
| Conventional Freehand | 29 | 1.31                | 0.43 |                 |         |         |

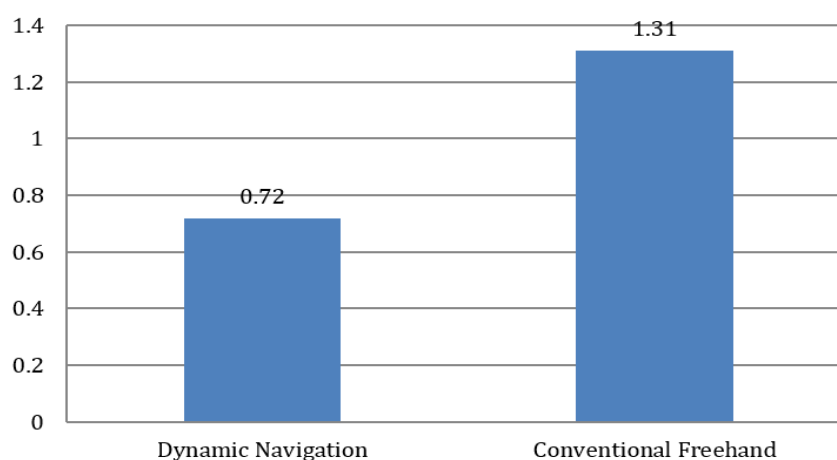


**Figure 3: Comparative Evaluation of Coronal Deviation between Dynamic Navigation and Conventional Freehand implant placement**

Table 4 & Figure 4 present the comparison of apical deviation between the study groups. The findings demonstrated that the Dynamic Navigation Group had a significantly lower mean apical deviation ( $0.91 \pm 0.31$  mm) than the Conventional Freehand Group ( $1.67 \pm 0.52$  mm). The mean difference in apical deviation between the two groups was 0.76 mm. Statistical analysis revealed a t value of 6.73, and the difference between the two study groups was

highly statistically significant ( $p < 0.001$ ). These findings indicate that the Dynamic Navigation technique achieved significantly greater accuracy at the apical level compared with the Conventional Freehand technique, demonstrating substantially less deviation from the virtually planned implant position. Overall, the results support the superior positional accuracy of dynamic navigation for implant placement at the apical level.

**Table 4: Comparison of Apical Deviation Between the Study Groups**

| Group                 | N  | Mean deviation (mm) | SD   | Mean difference | t value | P value |
|-----------------------|----|---------------------|------|-----------------|---------|---------|
| Dynamic Navigation    | 29 | 0.91                | 0.31 | 0.76            | 6.73    | <0.001  |
| Conventional Freehand | 29 | 1.67                | 0.52 |                 |         |         |

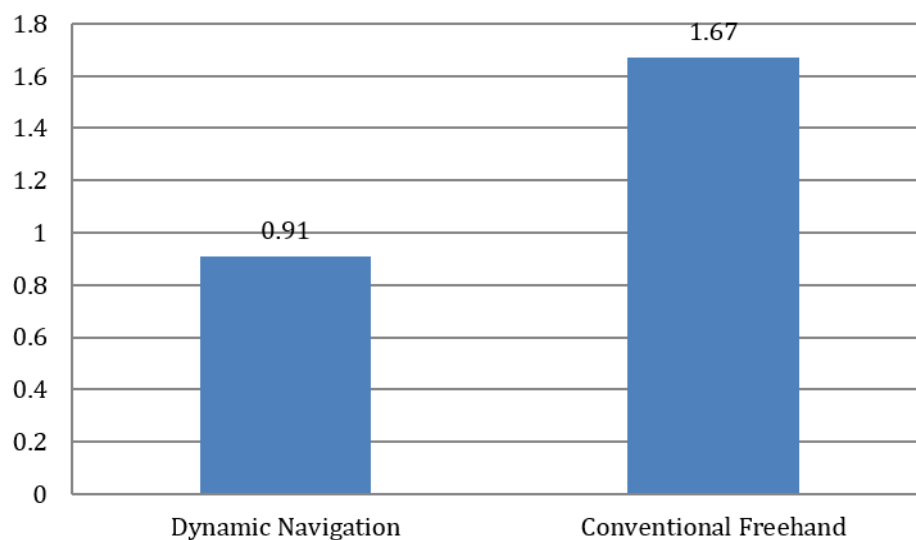


**Figure 4: Comparison of apical deviation between the Dynamic Navigation and Conventional Freehand groups**

Table 5 and Figure 5 present the comparison of angular deviation between the study groups. The findings demonstrated that the Dynamic Navigation Group had a significantly lower mean angular deviation ( $2.18 \pm 0.86^\circ$ ) than the Conventional Freehand Group ( $5.14 \pm 1.72^\circ$ ). The mean difference in angular deviation between the two groups was 2.96 degrees.

Statistical analysis revealed a t value of 8.27, and the difference between the two study groups

was highly statistically significant ( $p < 0.001$ ). These findings indicate that the Dynamic Navigation technique achieved significantly greater angular accuracy compared with the Conventional Freehand technique, with considerably less deviation from the virtually planned implant angulation. Overall, the results demonstrate the superior accuracy of dynamic navigation in controlling the angular orientation of dental implants during placement.

**Table 5: Comparison of Angular Deviation Between the Study Groups**

| Group                 | N  | Mean angular deviation (degrees) | SD   | Mean difference | t value | P value |
|-----------------------|----|----------------------------------|------|-----------------|---------|---------|
| Dynamic Navigation    | 29 | 2.18                             | 0.86 | 2.96            | 8.27    | <0.001  |
| Conventional Freehand | 29 | 5.14                             | 1.72 |                 |         |         |

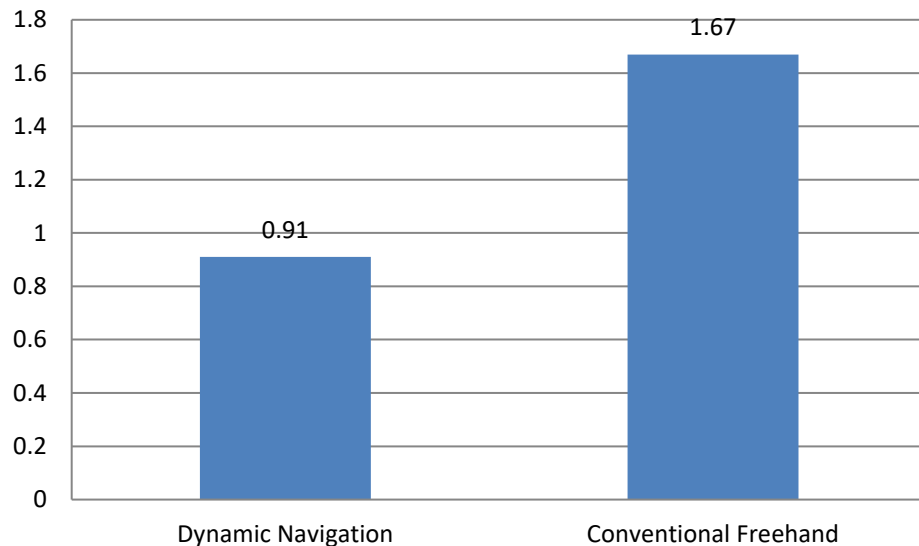
**Figure 6: Comparison of angular deviation between the Dynamic Navigation and Conventional Freehand groups**

Table 6 & Figure 6 present the comparison of depth deviation between the study groups. The findings demonstrated that the Dynamic Navigation Group had a significantly lower mean depth deviation ( $0.64 \pm 0.27$  mm) than the Conventional Freehand Group ( $1.08 \pm 0.39$  mm). The mean difference in depth deviation between the two groups was 0.44 mm.

Statistical analysis revealed a t value of 4.99, and the difference between the two study groups

was highly statistically significant ( $p < 0.001$ ). These findings indicate that the Dynamic Navigation technique achieved significantly greater accuracy in controlling implant placement depth compared with the Conventional Freehand technique, with considerably less deviation from the virtually planned implant depth. Overall, the results demonstrate the superior accuracy and precision of dynamic navigation for achieving the intended depth during dental implant placement.

**Table 6: Comparison of Depth Deviation Between the Study Groups**

| Group                 | N  | Mean depth deviation (mm) | SD   | Mean difference | t value | P value |
|-----------------------|----|---------------------------|------|-----------------|---------|---------|
| Dynamic Navigation    | 29 | 0.64                      | 0.27 | 0.44            | 4.99    | <0.001  |
| Conventional Freehand | 29 | 1.08                      | 0.39 |                 |         |         |

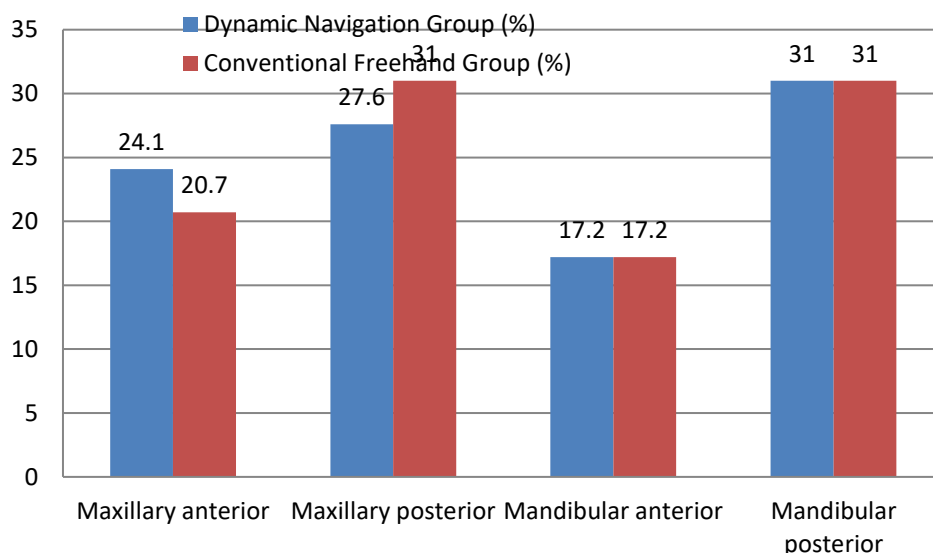


**Figure 6: Comparison of depth deviation between the Dynamic Navigation and Conventional Freehand groups**

Table 7 & Figure 7 present the overall comparison of implant placement accuracy parameters. The findings demonstrated consistently superior accuracy in the Dynamic Navigation Group compared with the Conventional Freehand Group across all evaluated parameters.

The mean coronal deviation was significantly lower in the Dynamic Navigation Group ( $0.72 \pm 0.24$  mm) than in the Conventional Freehand Group ( $1.31 \pm 0.43$  mm), with a mean difference of 0.59 mm ( $p < 0.001$ ). Similarly, the mean apical deviation was  $0.91 \pm 0.31$  mm in the Dynamic Navigation Group compared with  $1.67 \pm 0.52$  mm in the Conventional Freehand Group, resulting in a mean difference of 0.76 mm, which was highly statistically significant ( $p < 0.001$ ).

For angular deviation, the Dynamic Navigation Group demonstrated a substantially lower mean value of  $2.18 \pm 0.86^\circ$ , compared with  $5.14 \pm 1.72^\circ$  in the Conventional Freehand Group. The mean difference of  $2.96^\circ$  was highly statistically significant ( $p < 0.001$ ). Likewise, the mean depth deviation was significantly lower with dynamic navigation ( $0.64 \pm 0.27$  mm) than with the conventional freehand technique ( $1.08 \pm 0.39$  mm), with a mean difference of 0.44 mm ( $p < 0.001$ ).

Overall, all four implant placement accuracy parameters—coronal deviation, apical deviation, angular deviation, and depth deviation—were significantly lower in the Dynamic Navigation Group. These findings demonstrate that dynamic navigation provides significantly greater accuracy and precision in reproducing the virtually planned implant position compared with the conventional freehand technique.

**Table 7: Overall Comparison of Implant Placement Accuracy Parameters**

| Accuracy parameter             | Dynamic Navigation Mean $\pm$ SD | Conventional Freehand Mean $\pm$ SD | Mean difference | P value |
|--------------------------------|----------------------------------|-------------------------------------|-----------------|---------|
| Coronal deviation (mm)         | $0.72 \pm 0.24$                  | $1.31 \pm 0.43$                     | 0.59            | <0.001  |
| Apical deviation (mm)          | $0.91 \pm 0.31$                  | $1.67 \pm 0.52$                     | 0.76            | <0.001  |
| Angular deviation ( $^\circ$ ) | $2.18 \pm 0.86$                  | $5.14 \pm 1.72$                     | 2.96            | <0.001  |
| Depth deviation (mm)           | $0.64 \pm 0.27$                  | $1.08 \pm 0.39$                     | 0.44            | <0.001  |

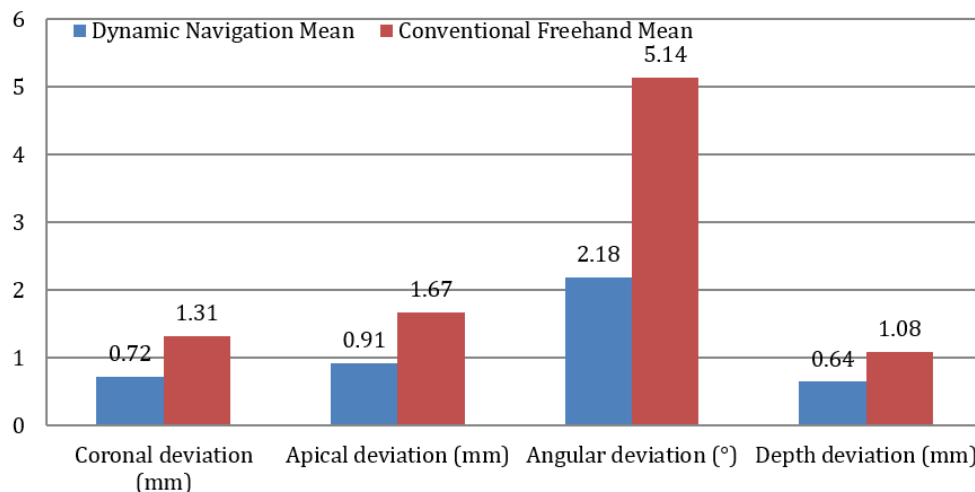


**Figure 7: Overall comparison of implant placement accuracy parameters between the Dynamic Navigation and Conventional Freehand group**

Table 8 & Figure 8 present the comparison of primary implant stability between the study groups. The findings demonstrated that the Dynamic Navigation Group had a slightly higher mean ISQ ( $73.24 \pm 4.86$ ) than the Conventional Freehand Group ( $71.41 \pm 5.15$ ). The mean difference between the two groups was 1.83 ISQ units. Statistical analysis revealed a t value of 1.39 and a p value of 0.170, indicating that the observed difference in primary implant stability between the two groups was not

statistically significant ( $p > 0.05$ ). Therefore, although the Dynamic Navigation Group demonstrated numerically higher primary implant stability, both techniques achieved comparable primary stability at the time of implant placement. These findings suggest that the significant improvements in positional accuracy observed with dynamic navigation did not translate into a statistically significant difference in primary implant stability compared with the conventional freehand technique.

**Table 8: Comparison of Primary Implant Stability Between the Study Groups**

| Group                 | N  | Mean ISQ | SD   | Mean difference | t value | P value |
|-----------------------|----|----------|------|-----------------|---------|---------|
| Dynamic Navigation    | 29 | 73.24    | 4.86 | 1.83            | 1.39    | 0.170   |
| Conventional Freehand | 29 | 71.41    | 5.15 |                 |         |         |

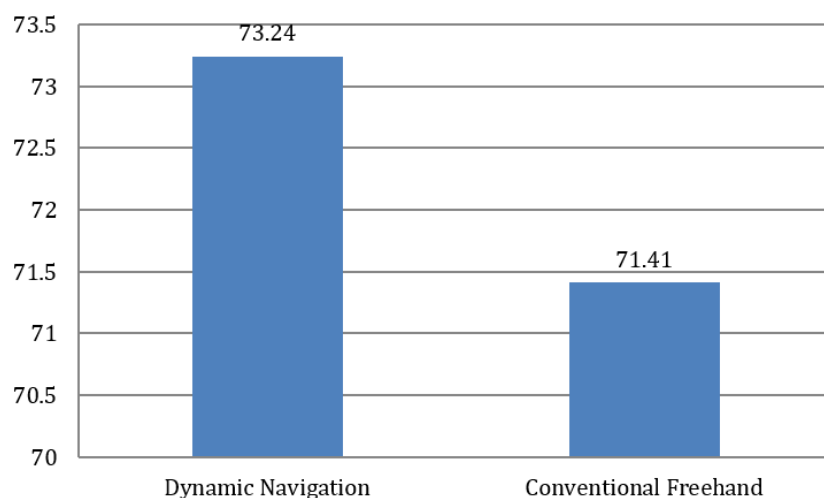


**Figure 8: Comparison of primary implant stability between the Dynamic Navigation and Conventional Freehand groups.**

Table 9 & Figure 9 present the comparison of prosthetic alignment between the study groups. The findings demonstrated a significantly more favorable distribution of prosthetic alignment outcomes in the Dynamic Navigation Group than in the Conventional Freehand Group. Ideal prosthetic alignment was achieved in 26 implants (89.7%) in the Dynamic Navigation Group, compared with 18 implants (62.1%) in the Conventional Freehand Group.

Minor correction was required for only 3 implants (10.3%) in the Dynamic Navigation Group, whereas 9 implants (31.0%) required minor correction in the Conventional Freehand Group. Furthermore, no implants (0.0%) in the Dynamic Navigation Group required major

correction, while 2 implants (6.9%) in the Conventional Freehand Group required major corrective measures.

The difference in prosthetic alignment outcomes between the two study groups was statistically significant ( $p = 0.014$ ). These findings indicate that dynamic navigation resulted in significantly better prosthetic alignment than the conventional freehand technique, with a higher proportion of ideally aligned implants and fewer cases requiring minor or major prosthetic correction. Overall, dynamic navigation appears to improve the prosthetically driven positioning of dental implants and may facilitate more predictable prosthetic rehabilitation.

**Table 9: Comparison of Prosthetic Alignment Between the Study Groups**

| Prosthetic alignment      | Dynamic Navigation n (%) | Conventional Freehand n (%) | Total n (%) | P value |
|---------------------------|--------------------------|-----------------------------|-------------|---------|
| Ideal                     | 26 (89.7)                | 18 (62.1)                   | 44 (75.9)   | 0.014   |
| Minor correction required | 3 (10.3)                 | 9 (31.0)                    | 12 (20.7)   |         |
| Major correction required | 0 (0.0)                  | 2 (6.9)                     | 2 (3.4)     |         |
| Total                     | 29 (100.0)               | 29 (100.0)                  | 58 (100.0)  |         |

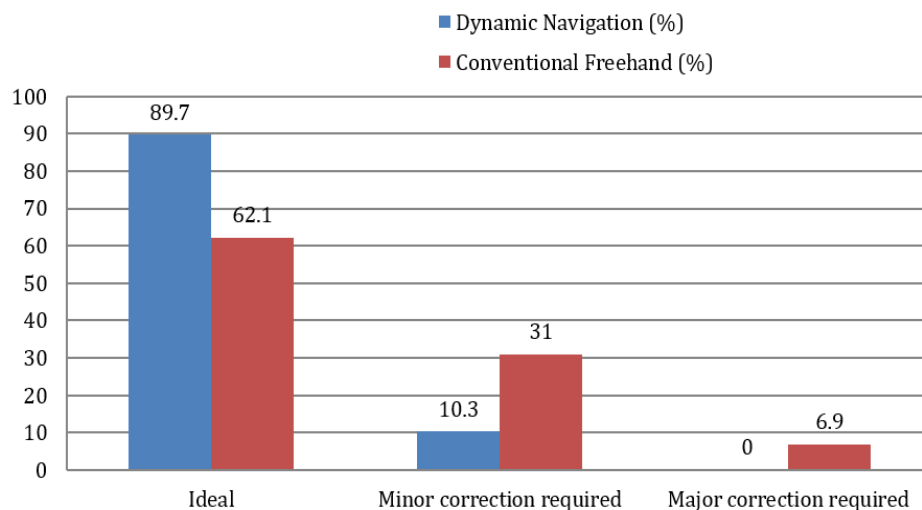


**Figure 9: Comparison of prosthetic alignment outcomes between the Dynamic Navigation and Conventional Freehand groups**

Table 10 & Figure 10 present the comparison of the emergence profile between the study groups. The findings demonstrated more favorable emergence profile outcomes in the Dynamic Navigation Group than in the Conventional

Freehand Group. An ideal emergence profile was achieved in 25 implants (86.2%) in the Dynamic Navigation Group, compared with 19 implants (65.5%) in the Conventional Freehand Group.

An acceptable emergence profile was observed in 4 implants (13.8%) in the Dynamic Navigation Group and 8 implants (27.6%) in the Conventional Freehand Group. Notably, none of the implants (0.0%) in the Dynamic

Navigation Group demonstrated a compromised emergence profile, whereas 2 implants (6.9%) in the Conventional Freehand Group were classified as compromised.

**Table 10: Comparison of Emergence Profile Between the Study Groups**

| Emergence profile | Dynamic Navigation n (%) | Conventional Freehand n (%) | Total n (%) | P value |
|-------------------|--------------------------|-----------------------------|-------------|---------|
| Ideal             | 25 (86.2)                | 19 (65.5)                   | 44 (75.9)   | 0.035   |
| Acceptable        | 4 (13.8)                 | 8 (27.6)                    | 12 (20.7)   |         |
| Compromised       | 0 (0.0)                  | 2 (6.9)                     | 2 (3.4)     |         |
| Total             | 29 (100.0)               | 29 (100.0)                  | 58 (100.0)  |         |

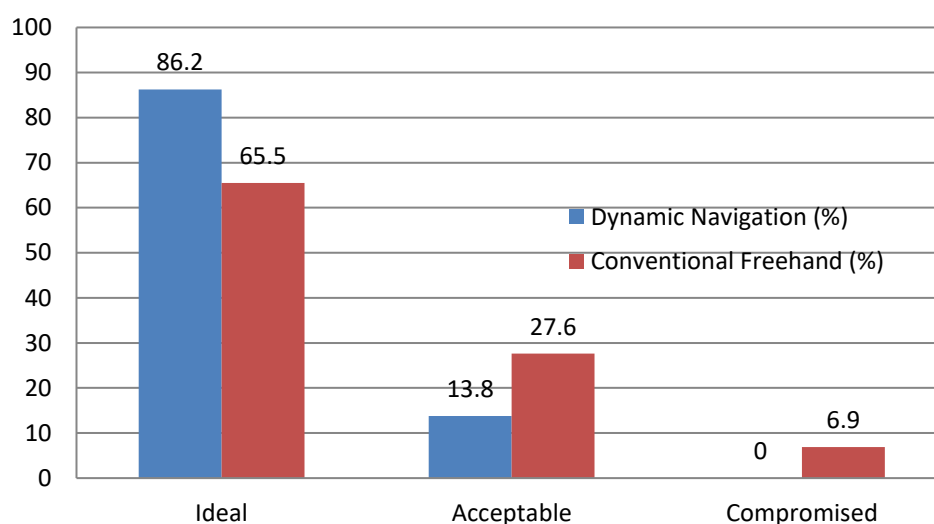


**Figure 10: Comparison of emergence profile outcomes between the Dynamic Navigation and Conventional Freehand groups**

Table 11 & Figure 11 present the comparison of the requirement for angled abutments between the study groups. The findings demonstrated a significantly lower requirement in the Dynamic Navigation Group compared with the Conventional Freehand Group. In the Dynamic Navigation Group, angled abutments were required for only 2 implants (6.9%), whereas 27 implants (93.1%) did not require angled abutments. In contrast, in the Conventional Freehand Group, angled abutments were required for 8 implants (27.6%), while 21 implants (72.4%) did not require them. The difference in angled abutment requirements

between the two study groups was statistically significant ( $p = 0.037$ ). These findings indicate that dynamic navigation significantly reduced the need for angled abutments compared with conventional freehand implant placement. The lower requirement for angled abutments in the Dynamic Navigation Group may be attributed to greater control over implant angulation and more accurate reproduction of the virtually planned implant position. Overall, dynamic navigation may facilitate more favorable prosthetic positioning and simplify subsequent prosthetic rehabilitation.

**Table 11:** Comparison of Requirement for Angled Abutments

| Angled requirement | Dynamic Navigation n (%) | Conventional Freehand n (%) | Total n (%) | P value |
|--------------------|--------------------------|-----------------------------|-------------|---------|
| Required           | 2 (6.9)                  | 8 (27.6)                    | 10 (17.2)   | 0.037   |
| Not required       | 27 (93.1)                | 21 (72.4)                   | 48 (82.8)   |         |
| Total              | 29 (100.0)               | 29 (100.0)                  | 58 (100.0)  |         |

Table 12 & Figure 12 present the comparison of surgical complications between the study groups. The findings demonstrate a lower frequency of complications in the Dynamic Navigation Group than in the Conventional Freehand Group. In the Dynamic Navigation Group, 27 implants (93.1%) were placed without any surgical complications, compared with 23 implants (79.3%) in the Conventional Freehand Group. Minor cortical perforation occurred in 1 case (3.4%) in the Dynamic Navigation Group and 3 cases (10.3%) in the Conventional Freehand Group. Excessive bleeding was reported in 1 case (3.4%) in the Dynamic Navigation Group compared with 2 cases (6.9%) in the Conventional Freehand

Group. No cases of adjacent structure proximity were observed in the Dynamic Navigation Group, whereas 1 case (3.4%) was reported in the Conventional Freehand Group. Although the Dynamic Navigation Group demonstrated a numerically lower incidence of surgical complications and a higher proportion of complication-free implant placements, the overall difference between the two study groups was not statistically significant ( $p = 0.129$ ). Therefore, both techniques showed statistically comparable surgical complication rates; however, a favorable trend toward fewer complications was observed with dynamic navigation.

**Table 12:** Comparison of Surgical Complications Between the Study Groups

| Surgical complication        | Dynamic Navigation n (%) | Conventional Freehand n (%) | P value |
|------------------------------|--------------------------|-----------------------------|---------|
| None                         | 27 (93.1)                | 23 (79.3)                   | 0.129   |
| Minor cortical perforation   | 1 (3.4)                  | 3 (10.3)                    |         |
| Excessive bleeding           | 1 (3.4)                  | 2 (6.9)                     |         |
| Adjacent structure proximity | 0 (0.0)                  | 1 (3.4)                     |         |

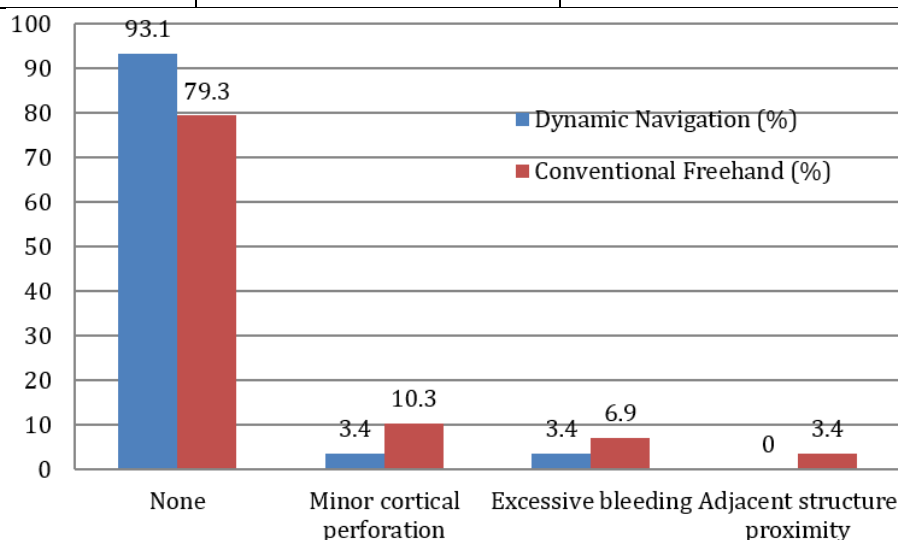
**Figure 12:** Comparison of Surgical Complications Between the Dynamic Navigation and Conventional Freehand Groups

Table 13 & Figure 13 present the comparison of prosthetic complications between the study groups. The findings demonstrate a lower frequency of prosthetic complications in the Dynamic Navigation Group compared with the Conventional Freehand Group. In the Dynamic Navigation Group, 27 implants (93.1%) had no prosthetic complications, compared with 22 implants (75.9%) in the Conventional Freehand Group.

Screw loosening was observed in 1 implant (3.4%) in the Dynamic Navigation Group and 2 implants (6.9%) in the Conventional Freehand Group. Prosthetic modification was required in only 1 implant (3.4%) in the Dynamic Navigation Group, compared with 4 implants (13.8%) in the Conventional Freehand Group.

Furthermore, no implants (0.0%) in the Dynamic Navigation Group required occlusal adjustment, whereas 1 implant (3.4%) in the Conventional Freehand Group required such adjustment.

Although the Dynamic Navigation Group demonstrated a higher proportion of complication-free cases and fewer prosthetic complications overall, the difference between the two study groups was not statistically significant ( $p = 0.071$ ). Therefore, both techniques demonstrated statistically comparable prosthetic complication rates; however, a favorable trend toward fewer complications and reduced need for prosthetic modifications was observed with dynamic navigation.

**Table 13: Comparison of Prosthetic Complications Between the Study Groups**

| Prosthetic complication          | Dynamic Navigation n (%) | Conventional Freehand n (%) | P value |
|----------------------------------|--------------------------|-----------------------------|---------|
| No complication                  | 27 (93.1)                | 22 (75.9)                   | 0.071   |
| Screw loosening                  | 1 (3.4)                  | 2 (6.9)                     |         |
| Prosthetic modification required | 1 (3.4)                  | 4 (13.8)                    |         |
| Occlusal adjustment required     | 0 (0.0)                  | 1 (3.4)                     |         |

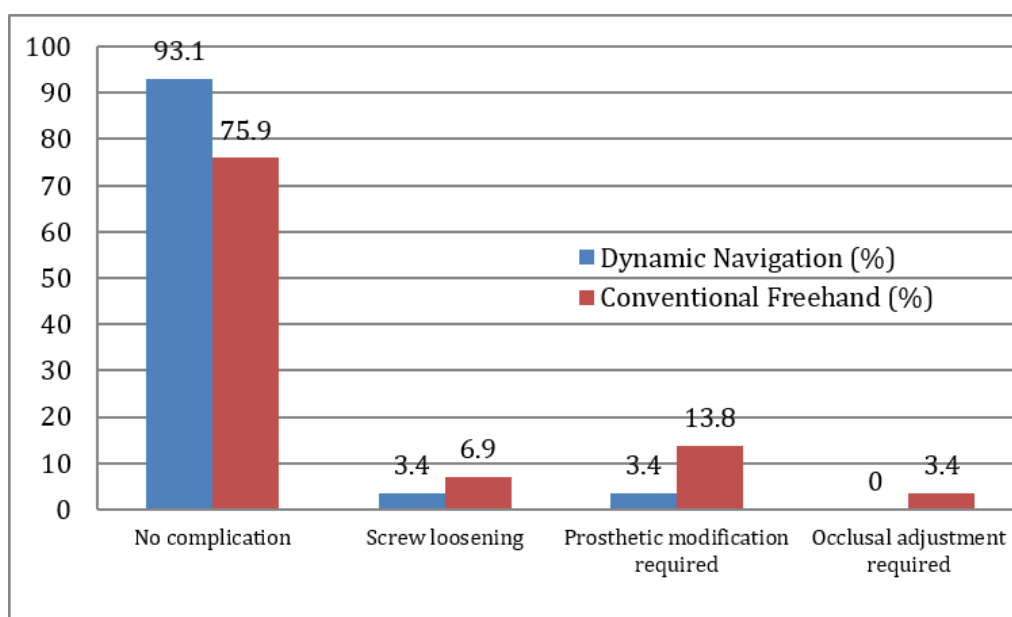


**Figure 13: Comparison of Prosthetic Complications Between the Dynamic Navigation and Conventional Freehand Groups**

Table 14 & Figure 14 present the comparison of marginal bone loss between the study groups. The findings revealed that the Dynamic Navigation Group demonstrated a lower mean marginal bone loss ( $0.48 \pm 0.21$  mm) than the Conventional Freehand Group ( $0.64 \pm 0.32$  mm). The mean difference between the two groups was 0.16 mm.

The independent samples t-test demonstrated a t value of 2.24 with a p value of 0.029, indicating that the difference in marginal bone loss between the two groups was statistically significant ( $p < 0.05$ ). Thus, implants placed

using the Dynamic Navigation technique exhibited significantly less marginal bone loss than those placed using the Conventional Freehand technique.

These findings suggest that the improved accuracy and precision of implant placement achieved with dynamic navigation may contribute to more favorable preservation of the peri-implant marginal bone. Overall, the Dynamic Navigation Group demonstrated significantly better marginal bone preservation compared with the Conventional Freehand Group.

**Table 14: Comparison of Marginal Bone Loss Between the Study Groups**

| Group                 | N  | Mean marginal bone loss (mm) | SD   | Mean difference | t value | P value |
|-----------------------|----|------------------------------|------|-----------------|---------|---------|
| Dynamic Navigation    | 29 | 0.48                         | 0.21 | 0.16            | 2.24    | 0.029   |
| Conventional Freehand | 29 | 0.64                         | 0.32 |                 |         |         |

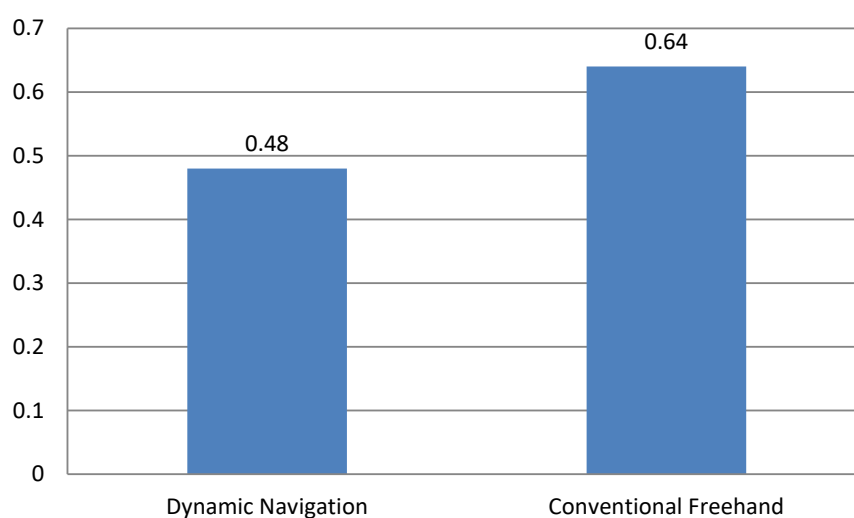


**Figure 14: Comparison of Marginal Bone Loss Between the Dynamic Navigation and Conventional Freehand Groups**

Table 15 & Figure 15 present the comparison of implant survival between the study groups. The findings demonstrated excellent implant survival outcomes in both groups. In the Dynamic Navigation Group, all 29 implants (100.0%) survived, with no implant failures reported. In the Conventional Freehand Group, 28 implants (96.6%) survived, while 1 implant (3.4%) failed. Overall, 57 of the 58 implants (98.3%) survived,

resulting in an overall implant failure rate of only 1.7%. Despite the numerically higher implant survival rate observed in the Dynamic Navigation Group (100.0%) compared with the Conventional Freehand Group (96.6%), the difference was not statistically significant ( $p = 1.000$ ). Therefore, both implant placement techniques demonstrated statistically comparable implant survival outcomes.

Overall, the findings indicate that both dynamic navigation and conventional freehand implant placement achieved high implant survival rates, with a favorable numerical trend toward complete survival in the Dynamic Navigation Group. However, the absence of a statistically

significant difference suggests that the superior positional accuracy of dynamic navigation did not translate into a demonstrable difference in short-term implant survival within the present sample.

**Table 15: Comparison of Implant Survival Between the Study Groups**

| Implant outcome | Dynamic Navigation n (%) | Conventional Freehand n (%) | Total n (%) | P value |
|-----------------|--------------------------|-----------------------------|-------------|---------|
| Survived        | 29 (100.0)               | 28 (96.6)                   | 57 (98.3)   | 1.000   |
| Failed          | 0 (0.0)                  | 1 (3.4)                     | 1 (1.7)     |         |
| Total           | 29 (100.0)               | 29 (100.0)                  | 58 (100.0)  |         |

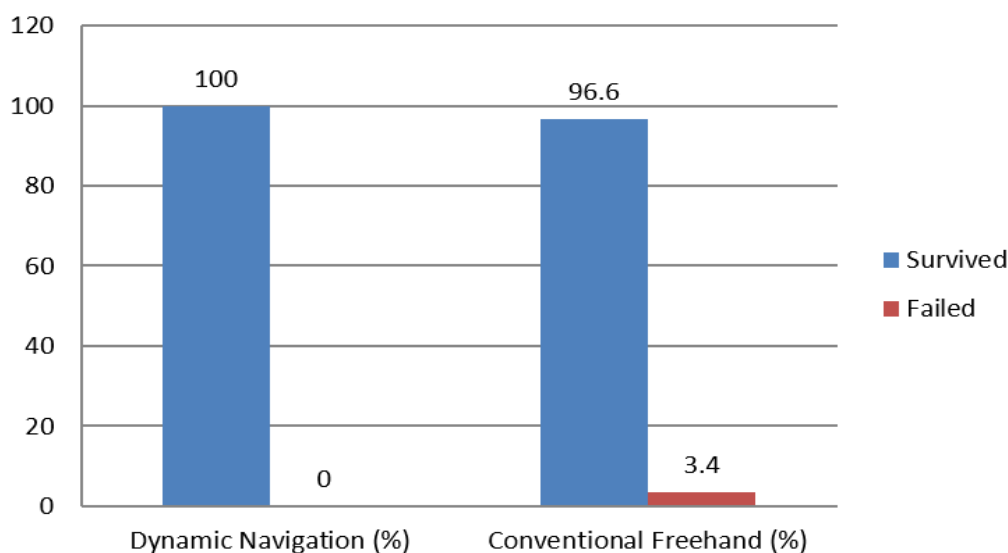


**Figure 15: Comparison of Implant Survival Between the Dynamic Navigation and Conventional Freehand Groups**

Table 16 & Figure 16 present the comparison of patient satisfaction scores between the study groups. The findings revealed that patients in the Dynamic Navigation Group reported consistently higher satisfaction scores across all assessed parameters than those in the Conventional Freehand Group. The mean score for surgical experience was significantly higher in the Dynamic Navigation Group ( $8.79 \pm 0.94$ ) than in the Conventional Freehand Group ( $7.93 \pm 1.19$ ), with a statistically significant difference ( $t = 3.06$ ,  $p = 0.003$ ). Similarly, postoperative comfort was significantly greater in the Dynamic Navigation Group, with a mean score of  $8.66 \pm 1.01$ , compared with  $7.86 \pm 1.27$  in the

Conventional Freehand Group ( $t = 2.65$ ,  $p = 0.010$ ).

With respect to esthetic satisfaction, the Dynamic Navigation Group recorded a significantly higher mean score of  $9.03 \pm 0.78$ , whereas the Conventional Freehand Group had a mean score of  $8.17 \pm 1.10$ . This difference was statistically significant ( $t = 3.44$ ,  $p = 0.001$ ). Furthermore, the mean overall satisfaction score was significantly higher in the Dynamic Navigation Group ( $8.93 \pm 0.80$ ) compared with the Conventional Freehand Group ( $8.00 \pm 1.07$ ), with the difference being highly statistically significant ( $t = 3.75$ ,  $p < 0.001$ ).

Overall, the findings demonstrate that dynamic navigation-guided implant placement resulted in significantly greater patient satisfaction than conventional freehand implant placement across all evaluated domains, including surgical experience, postoperative comfort, esthetic

satisfaction, and overall satisfaction. These results suggest that the enhanced accuracy and predictability associated with dynamic navigation may contribute to a more favorable overall treatment experience from the patient's perspective.

**Table 16: Comparison of Patient Satisfaction Scores Between the Study Groups**

| Satisfaction parameter | Dynamic Navigation Mean $\pm$ SD | Conventional Freehand Mean $\pm$ SD | t value | P value |
|------------------------|----------------------------------|-------------------------------------|---------|---------|
| Surgical experience    | 8.79 $\pm$ 0.94                  | 7.93 $\pm$ 1.19                     | 3.06    | 0.003   |
| Postoperative comfort  | 8.66 $\pm$ 1.01                  | 7.86 $\pm$ 1.27                     | 2.65    | 0.010   |
| Esthetic satisfaction  | 9.03 $\pm$ 0.78                  | 8.17 $\pm$ 1.10                     | 3.44    | 0.001   |
| Overall satisfaction   | 8.93 $\pm$ 0.80                  | 8.00 $\pm$ 1.07                     | 3.75    | <0.001  |

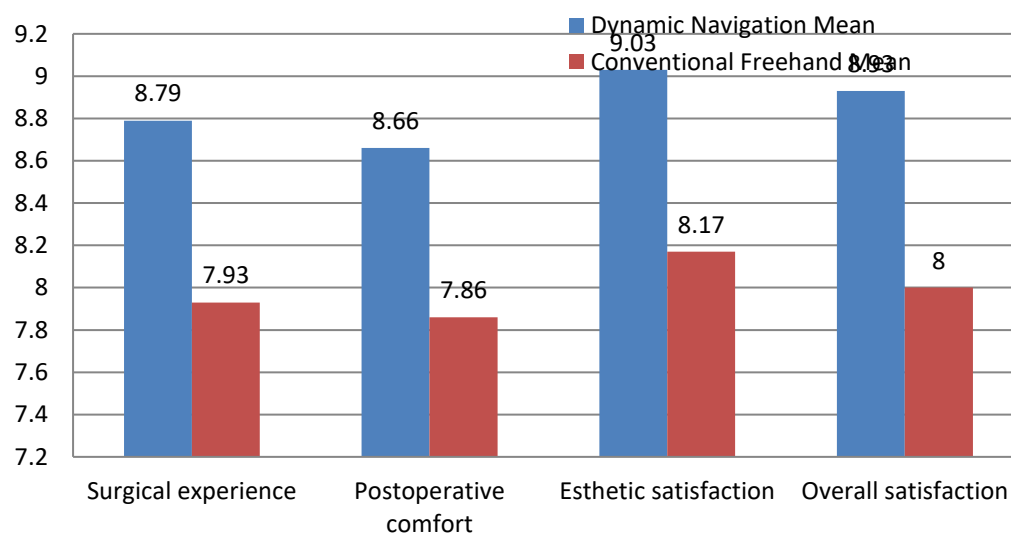


**Figure 16: Comparison of Patient Satisfaction Scores Between the Dynamic Navigation and Conventional Freehand Groups**

Table 17 presents the correlation analysis between implant placement deviations and the overall prosthetic outcome score. The findings demonstrated significant negative correlations for all evaluated implant placement accuracy parameters. These results indicate that as implant placement deviations increased, the overall prosthetic outcome score decreased, reflecting less favorable prosthetic outcomes with greater positional inaccuracies. Coronal deviation showed a moderate negative

correlation with the overall prosthetic outcome score ( $r = -0.521$ ,  $p < 0.001$ ), indicating that greater deviation at the coronal entry point was significantly associated with poorer prosthetic outcomes. Similarly, apical deviation demonstrated a moderate negative correlation ( $r = -0.487$ ,  $p < 0.001$ ), suggesting that increased apical displacement was associated with a reduction in the overall prosthetic outcome score.

Among all accuracy parameters, angular deviation exhibited the strongest negative correlation with the overall prosthetic outcome score ( $r = -0.614$ ,  $p < 0.001$ ). This strong and statistically significant association indicates that increasing angular discrepancy from the virtually planned implant position had the greatest adverse relationship with prosthetic outcomes.

Depth deviation also demonstrated a moderate negative correlation with the overall prosthetic outcome score ( $r = -0.436$ ,  $p = 0.001$ ), indicating that greater discrepancies in implant

placement depth were significantly associated with less favorable prosthetic outcomes.

Overall, all four implant placement deviations were significantly and negatively correlated with the overall prosthetic outcome score. Angular deviation showed the strongest association, followed by coronal deviation, apical deviation, and depth deviation. These findings suggest that greater precision in reproducing the virtually planned implant position, particularly with respect to implant angulation, is associated with improved prosthetic outcomes.

**Table 17: Correlation Between Implant Placement Deviations and Overall Prosthetic Outcome Score**

| Accuracy parameter | Pearson's correlation coefficient (r) | P value | Interpretation                |
|--------------------|---------------------------------------|---------|-------------------------------|
| Coronal deviation  | -0.521                                | <0.001  | Moderate negative correlation |
| Apical deviation   | -0.487                                | <0.001  | Moderate negative correlation |
| Angular deviation  | -0.614                                | <0.001  | Strong negative correlation   |
| Depth deviation    | -0.436                                | 0.001   | Moderate negative correlation |

Table 18 presents the overall summary of primary and secondary outcomes demonstrated that the Dynamic Navigation Group achieved significantly better results than the Conventional Freehand Group across most evaluated parameters.

With respect to implant placement accuracy, the Dynamic Navigation Group demonstrated significantly lower coronal deviation ( $0.72 \pm 0.24$  mm vs.  $1.31 \pm 0.43$  mm), apical deviation ( $0.91 \pm 0.31$  mm vs.  $1.67 \pm 0.52$  mm), angular deviation ( $2.18 \pm 0.86^\circ$  vs.  $5.14 \pm 1.72^\circ$ ), and depth deviation ( $0.64 \pm 0.27$  mm vs.  $1.08 \pm 0.39$  mm) compared with the Conventional Freehand Group. All differences in implant placement accuracy were highly statistically significant ( $p < 0.001$ ), demonstrating superior positional accuracy with dynamic navigation.

Regarding prosthetic outcomes, ideal prosthetic alignment was achieved in 89.7% of implants in the Dynamic Navigation Group compared with 62.1% in the Conventional Freehand Group,

and the difference was statistically significant ( $p = 0.014$ ). Similarly, an ideal emergence profile was observed more frequently in the Dynamic Navigation Group (86.2%) than in the Conventional Freehand Group (65.5%), with a statistically significant difference ( $p = 0.035$ ). The requirement for angled abutments was significantly lower with dynamic navigation (6.9%) than with the conventional freehand technique (27.6%;  $p = 0.037$ ).

The Dynamic Navigation Group also exhibited significantly lower marginal bone loss ( $0.48 \pm 0.21$  mm) compared with the Conventional Freehand Group ( $0.64 \pm 0.32$  mm), with the difference reaching statistical significance ( $p = 0.029$ ). In contrast, implant survival was excellent in both groups, with survival rates of 100.0% in the Dynamic Navigation Group and 96.6% in the Conventional Freehand Group. This difference was not statistically significant ( $p = 1.000$ ).

Furthermore, patients treated using dynamic navigation reported significantly higher overall satisfaction scores ( $8.93 \pm 0.80$ ) than those treated using the conventional freehand technique ( $8.00 \pm 1.07$ ), with the difference being highly statistically significant ( $p < 0.001$ ).

Overall, the findings demonstrate that dynamic navigation significantly improved implant placement accuracy, prosthetic alignment, emergence profile, marginal bone preservation,

and patient satisfaction while reducing the requirement for angled abutments compared with conventional freehand implant placement. Although implant survival rates were statistically comparable between the

groups, the collective findings strongly support the superior accuracy and prosthetic predictability of dynamic navigation-guided implant placement.

**Table 18: Overall Summary of Primary and Secondary Outcomes**

| Outcome                           | Dynamic Navigation Group | Conventional Freehand Group | P value  | Significance    |
|-----------------------------------|--------------------------|-----------------------------|----------|-----------------|
| Coronal deviation (mm)            | $0.72 \pm 0.24$          | $1.31 \pm 0.43$             | $<0.001$ | Significant     |
| Apical deviation (mm)             | $0.91 \pm 0.31$          | $1.67 \pm 0.52$             | $<0.001$ | Significant     |
| Angular deviation ( $^{\circ}$ )  | $2.18 \pm 0.86$          | $5.14 \pm 1.72$             | $<0.001$ | Significant     |
| Depth deviation (mm)              | $0.64 \pm 0.27$          | $1.08 \pm 0.39$             | $<0.001$ | Significant     |
| Ideal prosthetic alignment, n (%) | 26 (89.7)                | 18 (62.1)                   | 0.014    | Significant     |
| Ideal emergence profile, n (%)    | 25 (86.2)                | 19 (65.5)                   | 0.035    | Significant     |
| Angled abutment required, n (%)   | 2 (6.9)                  | 8 (27.6)                    | 0.037    | Significant     |
| Marginal bone loss (mm)           | $0.48 \pm 0.21$          | $0.64 \pm 0.32$             | 0.029    | Significant     |
| Implant survival, n (%)           | 29 (100.0)               | 28 (96.6)                   | 1.000    | Not significant |
| Overall patient satisfaction      | $8.93 \pm 0.80$          | $8.00 \pm 1.07$             | $<0.001$ | Significant     |

## Discussion

The present study assessed the accuracy of dynamic navigation systems in implant surgery and their effect on prosthetic outcomes. The findings demonstrated that dynamic navigation facilitated precise implant placement with minimal positional discrepancies between the

planned and actual implant locations. This high level of surgical precision translated into improved prosthetic alignment, favorable emergence profiles, and predictable functional as well as esthetic rehabilitation. These results further strengthen the evidence that dynamic navigation is a dependable digital technology

capable of accurately transferring virtual implant planning into clinical practice.

Precise three-dimensional implant positioning remains one of the most important determinants of successful implant-supported rehabilitation. Inaccuracies in implant angulation, depth, or mesiodistal positioning may compromise prosthetic fit, occlusal load distribution, peri-implant tissue health, esthetics, and ultimately long-term implant success. The low positional deviations observed in the present investigation indicate that dynamic navigation enables excellent intraoperative control throughout osteotomy preparation and implant placement. Similar conclusions were drawn by Jung et al. (2009) [2], who recognized computer-assisted technologies as a major advancement in implant dentistry by facilitating prosthetically driven treatment planning and improving surgical precision. Likewise, Tahmaseb et al. (2018) [1] reported that computer-assisted implant surgery consistently demonstrates greater placement accuracy than conventional freehand techniques.

A notable advantage identified in the present study was the ability of the navigation system to provide continuous real-time feedback during surgery. Unlike static surgical guides, which restrict implant placement to a predefined drilling pathway, dynamic navigation enables the clinician to make immediate adjustments while maintaining the planned implant trajectory. Such flexibility is particularly valuable when anatomical variations or intraoperative challenges are encountered. Block and Emery (2016) [4] similarly described dynamic navigation as combining the precision of digital planning with the adaptability of freehand surgery, thereby allowing modification of implant positioning without sacrificing accuracy. Correspondingly, Gargallo-Albiol et al. (2019) [3] concluded that navigation-assisted surgery offers considerable advantages in complex implant cases, although successful application depends on adequate operator training and familiarity with the technology.

The high level of implant placement accuracy achieved in the present study corresponds well

with previous clinical investigations evaluating navigation-assisted surgery. Stefanelli et al. (2019) [6] demonstrated that dynamic navigation can accurately reproduce the planned implant position in routine clinical practice, highlighting its practical reliability. Similarly, Wei et al. (2021) [5] reported through a systematic review and meta-analysis that dynamic navigation consistently results in minimal coronal, apical, and angular deviations while achieving an accuracy comparable to that of static guided implant surgery.

Another important finding of this investigation was the positive influence of accurate implant positioning on prosthetic rehabilitation. Proper implant angulation and depth simplified prosthetic procedures by facilitating passive prosthesis fit, ideal emergence profiles, and minimizing the requirement for angled abutments or corrective restorative procedures. Furthermore, precise implant positioning contributes to more favorable biomechanical load distribution and reduces the likelihood of mechanical and biological complications. These observations are consistent with the conclusions of Pellegrino et al. (2021) [7], who demonstrated that dynamic navigation significantly enhances implant placement accuracy and supports more predictable prosthetic rehabilitation.

The favorable prosthetic outcomes observed in the present study are further supported by the findings of Jorba-García et al. (2021) [9], who reported excellent positional precision and significantly reduced angular deviations using dynamic computer-assisted implant surgery. Likewise, Wang et al. (2021) [8] demonstrated that navigation systems consistently improve implant placement accuracy across a variety of clinical situations, thereby increasing both surgical precision and restorative predictability.

In addition to improving surgical precision, accurate implant positioning achieved through dynamic navigation contributes substantially to prosthetically driven rehabilitation. Proper implant orientation optimizes screw-access location, enhances crown contour and emergence profile, facilitates oral hygiene

maintenance, and supports long-term peri-implant soft tissue stability. Similar observations were made by Pellegrino et al. (2021) [10], who concluded that navigation-assisted implant surgery enhances both surgical accuracy and restorative predictability while maintaining excellent clinical safety.

The findings of the present investigation are also supported by earlier evidence regarding computer-guided implant surgery. Schneider et al. (2009) [11] demonstrated that computer-guided implant placement significantly reduces positional deviations compared with conventional implant placement methods, although clinical accuracy remains dependent upon multiple technical and operator-related variables. Likewise, Van Assche et al. (2012) [12] reported that computer-aided implant placement improves surgical precision and decreases the risk of injury to adjacent anatomical structures, thereby enhancing procedural safety.

Apart from improving positional accuracy, digital guidance also facilitates minimally invasive surgical approaches and may improve clinical efficiency. Vercruyssen et al. (2014) [13] emphasized that guided implant surgery supports flapless procedures while improving treatment accuracy and efficiency, potentially resulting in reduced postoperative discomfort and accelerated healing. Similarly, Block et al. (2017) [14] demonstrated that dynamic navigation enables highly accurate implant placement with minimal coronal, apical, and angular deviations, while increasing clinician confidence through continuous real-time visualization of implant trajectory.

Another important clinical observation was the potential improvement in surgical efficiency associated with navigation-assisted implant placement. Although dynamic navigation requires an initial learning curve, procedural efficiency appears to improve substantially with increasing operator experience. Sun et al. (2020) [15] similarly reported that navigation-assisted implant surgery may shorten operative time once clinicians become proficient with the

system while maintaining excellent placement accuracy.

Despite these advantages, several factors continue to influence the overall precision of dynamic navigation systems. Accurate registration, high-quality CBCT imaging, precise calibration, patient stability during surgery, bone quality, and operator experience remain critical determinants of clinical accuracy. Zhou et al. (2018) [16] also identified these variables as significant contributors to the success of guided implant surgery and emphasized the importance of meticulous treatment planning, accurate system calibration, and comprehensive clinician training for achieving predictable outcomes. Zhou et al. (2018) [16] identified these variables as significant contributors to the success of guided implant surgery and emphasized the importance of meticulous treatment planning, accurate system calibration, and comprehensive clinician training for achieving predictable outcomes. Similarly, D'haese et al. (2017) [17] reported that the accuracy of computer-assisted implant surgery is influenced by multiple factors, including imaging quality, data acquisition, guide or navigation workflow, surgical execution, and operator experience, underscoring the importance of standardized digital protocols and adequate clinical training.

Overall, the findings of the present study demonstrate that dynamic navigation is a highly accurate and clinically reliable approach for dental implant placement. By integrating prosthetically driven digital planning with real-time intraoperative guidance, the technique enables precise implant positioning, improves prosthetic outcomes, and supports minimally invasive treatment while maintaining surgical flexibility. Although successful implementation requires appropriate clinician training and adherence to digital workflow protocols, dynamic navigation represents a valuable advancement in implant dentistry. Further multicenter studies with larger sample sizes and longer follow-up periods are needed to evaluate its long-term effects on implant survival, peri-implant tissue health, prosthetic longevity,

patient-reported outcomes, and cost-effectiveness.

### Limitations

Several limitations should be considered while interpreting the findings of this study. The research was conducted at a single tertiary care institution and involved a relatively small sample, which may restrict the broader applicability of the results. Because the duration of follow-up was limited, the long-term performance of implants, peri-implant tissue stability, and prosthetic durability could not be comprehensively evaluated. Surgical accuracy may also have been influenced by the operator's proficiency with the dynamic navigation system, as successful implementation of this technology depends on adequate training and clinical experience. In addition, the study population mainly consisted of partially edentulous patients, and therefore the outcomes may not fully reflect the effectiveness of dynamic navigation in completely edentulous individuals or in complex implant cases requiring extensive hard- and soft-tissue augmentation. The economic impact of incorporating navigation technology into routine clinical practice, including installation, maintenance, and training expenses, was beyond the scope of this investigation. Moreover, patient-reported outcomes were assessed only during the early postoperative period and did

not include long-term functional performance or oral health-related quality-of-life measures. Further well-designed multicenter studies with larger cohorts and prolonged follow-up are required to validate these findings and establish the long-term clinical, prosthetic, and economic value of dynamic navigation in implant dentistry.

### Conclusion

Dynamic navigation systems provide highly accurate and predictable implant placement by enabling real-time guidance and precise execution of prosthetically driven treatment plans. Compared with conventional freehand surgery, dynamic navigation significantly reduces positional deviations, enhances prosthetic fit, and minimizes the likelihood of surgical complications. These improvements contribute to more favorable restorative outcomes and greater treatment predictability. Although implementation requires specialized training, additional operative planning, and greater financial investment, the technology offers substantial clinical benefits, particularly in anatomically challenging cases and esthetically demanding regions. Future multicenter studies with larger sample sizes and extended follow-up are warranted to validate long-term clinical performance, cost-effectiveness, and patient-centered outcomes.

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