

3D Orthodontic Optimization of Implant Sites and Its Influence on Implant Position, Peri-Implant Tissue Health, and Prosthetic Esthetics: A Prospective Clinical Study

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ABSTRACT:

Background:

Precise implant positioning is essential for achieving favorable peri-implant tissue health and prosthetic esthetics. Orthodontic optimization of the implant site may improve the spatial conditions required for accurate three-dimensional (3D) implant placement.

Aim:

To evaluate the influence of 3D orthodontic optimization of implant sites on implant-position accuracy, peri-implant tissue health, marginal bone changes, and prosthetic esthetic outcomes compared with conventional implant planning.

Materials and Methods:

A total of 40 patients requiring maxillary anterior implant rehabilitation were included and divided equally into two groups. Group A (n = 20) underwent 3D orthodontic optimization before implant placement, whereas Group B (n = 20) received conventional implant planning. 3D deviations between planned and achieved implant positions were assessed, including coronal, apical, vertical, mesiodistal, buccolingual, and angular deviations. At 6 months, peri-implant tissue parameters, marginal bone changes, implant survival, complications, and esthetic outcomes using the Pink Esthetic Score (PES) and White Esthetic Score (WES) were evaluated. Correlation and multivariable regression analyses were performed to identify factors associated with PES.

Results:

The optimized group demonstrated significantly lower coronal, apical, vertical, mesiodistal, buccolingual, and angular deviations than the conventional group ($p \leq 0.002$). A greater proportion of implants achieved the predefined positional accuracy criteria in the optimized group. At 6 months, Group A showed lower modified plaque index and probing depth

and greater keratinized mucosal width and mucosal thickness ($p < 0.05$). Mean marginal bone change was also significantly lower in Group A (0.29 ± 0.17 mm vs. 0.46 ± 0.24 mm; $p = 0.008$). PES, WES, and combined PES + WES scores were significantly higher following 3D optimization ($p \leq 0.005$). Angular deviation and coronal deviation were negatively correlated with PES, whereas mucosal thickness showed a positive correlation. Regression analysis identified 3D orthodontic optimization and mucosal thickness as positive predictors of PES.

Conclusion:

3D orthodontic optimization of implant sites was associated with greater implant-position accuracy, more favorable peri-implant tissue characteristics, reduced marginal bone changes, and improved prosthetic esthetic outcomes at 6 months. Integrating orthodontic site optimization with 3D implant planning may enhance the predictability of anterior implant rehabilitation.

Keywords: Anterior dental implants, Implant positioning, Orthodontic optimization, Peri-implant tissue, Prosthetic esthetics, Three-dimensional planning

Introduction

Dental implant therapy has become a widely accepted treatment modality for the replacement of missing teeth, providing predictable functional and esthetic outcomes when appropriate surgical and restorative principles are followed [1]. Successful implant rehabilitation depends not only on osseointegration but also on the accurate three-dimensional (3D) positioning of the implant in relation to the adjacent dentition, alveolar bone, and peri-implant soft tissues. The position of the implant is particularly important in esthetically demanding areas, where deviations from the ideal position may influence the emergence profile, prosthetic contours, and overall appearance of the restoration.

Following tooth extraction, remodeling of the alveolar ridge can produce progressive horizontal and vertical dimensional changes, potentially reducing the anatomical volume available for subsequent implant placement [2]. These changes may be accompanied by alterations in the position and angulation of adjacent teeth, resulting in inadequate mesiodistal space, unfavorable root proximity, or compromised implant trajectories. Such anatomical limitations can make conventional implant placement difficult and may prevent achievement of a prosthetically driven implant position.

The relationship between implant position and the surrounding peri-implant tissues is also critical for maintaining long-term biological stability. Placement of an implant in an unfavorable 3D position may compromise facial bone support and contribute to deficiencies in the peri-implant soft-tissue architecture [3]. Therefore, appropriate preparation of the implant site before surgery is essential for

establishing favorable biological conditions and maintaining the integrity of the tissues surrounding the implant.

Orthodontic treatment provides an effective approach for modifying the local dental environment before implant placement. Controlled movement of adjacent teeth can improve mesiodistal space, correct unfavorable root angulation, and establish an appropriate spatial relationship for the future implant [4]. Orthodontic site development may consequently transform an anatomically compromised implant site into a more favorable environment for prosthetically oriented implant rehabilitation.

The integration of orthodontic and implant treatment is particularly important when tooth position or root inclination limits the available space for implant placement. By coordinating tooth movement with the anticipated implant position, the clinician can establish adequate root separation and optimize the distribution of available space before surgical intervention [5]. This interdisciplinary approach permits the implant position to be determined according to the desired restorative outcome rather than being dictated solely by the pre-existing dental anatomy.

Recent developments in digital dentistry have further enhanced the ability to evaluate and plan implant sites in 3D. Cone-beam computed tomography (CBCT) allows assessment of alveolar bone dimensions, root position, and the relationship of the prospective implant site to important anatomical structures [6]. In addition, digital models and intraoral scanning can provide detailed information regarding tooth position, arch form, occlusal relationships, and available restorative space.

Combining these diagnostic modalities can facilitate more precise orthodontic and implant treatment planning.

Prosthetically driven implant placement is essential for achieving a harmonious emergence profile and favorable crown morphology. Even when osseointegration is successfully achieved, an implant positioned outside the appropriate restorative envelope may result in unfavorable prosthetic contours and compromised esthetic integration [7]. Consequently, optimization of the implant site should consider not only the available bone but also the anticipated prosthetic requirements and the 3D position of the final restoration.

The use of 3D treatment planning has created opportunities for more accurate coordination between orthodontic tooth movement and implant placement. Digital planning can allow the desired final tooth and implant positions to be visualized before treatment, facilitating identification of spatial deficiencies and modification of the dental anatomy before implant surgery [8]. Such an approach may improve communication among orthodontic, surgical, and prosthodontic disciplines and support a more coordinated treatment sequence.

Despite these advances, the clinical relationship between orthodontically optimized implant sites and subsequent implant positioning, peri-implant tissue health, and prosthetic esthetics has not been sufficiently established. The need for prospective clinical evaluation is particularly relevant because improvements in available space and root positioning may not necessarily translate into equivalent improvements in surgical accuracy or restorative outcomes. A comprehensive assessment of these parameters may therefore provide clinically meaningful evidence regarding the value of 3D orthodontic site optimization [9].

Therefore, the present prospective clinical study was designed to evaluate the influence of 3D orthodontic optimization of implant sites on implant position, peri-implant tissue health, and prosthetic esthetic outcomes. The study specifically aimed to determine whether orthodontic preparation of the implant site could improve the accuracy and spatial positioning of implants while contributing to favorable biological and esthetic outcomes following implant-supported rehabilitation.

Materials & Methods

Study Design and Participants

The present study was designed as a prospective comparative clinical study to evaluate the effect of 3D orthodontic optimization of implant sites on implant-position accuracy, peri-implant tissue health, marginal bone changes, and prosthetic esthetic outcomes. A total of 40 patients requiring implant-supported rehabilitation in the maxillary anterior region were included. Participants were equally allocated into two groups, with 20 patients in each group.

Group A (3D Orthodontic Optimization Group) underwent orthodontic optimization of the implant site before implant placement. The orthodontic intervention was directed toward achieving a favorable 3D position of the adjacent teeth and creating an anatomically appropriate implant site for subsequent implant placement.

Group B (Conventional Implant Planning Group) underwent conventional implant-site assessment and implant planning without prior 3D orthodontic optimization.

The study population consisted of young and middle-aged adults, with a mean overall age of approximately 29 years. The implant sites included the maxillary central incisors, lateral incisors, and canines. Baseline implant-site width was recorded before treatment to ensure comparability between the groups.

Eligibility Criteria

Patients requiring replacement of a single missing tooth in the maxillary anterior region and considered suitable for implant-supported rehabilitation were eligible for inclusion. Patients were required to have adequate systemic and local conditions for implant placement and to complete the planned clinical and radiographic follow-up.

Patients with conditions that could substantially compromise implant placement, peri-implant tissue healing, or esthetic assessment were excluded. Cases with inadequate follow-up or incomplete clinical or radiographic records were also excluded from the final analysis.

Baseline Clinical Assessment

At baseline, demographic and clinical information was recorded for all participants. The following parameters were documented:

- Age and sex
- Implant site
- Baseline implant-site width

- Condition of the edentulous ridge and surrounding teeth
- Available soft-tissue dimensions
- Radiographic characteristics relevant to implant planning

The baseline implant-site dimensions were evaluated before implant placement. These measurements were used to assess the comparability of the two treatment groups.

3D Orthodontic Optimization and Implant Planning

For patients in Group A, the implant site was orthodontically optimized in 3D before implant placement. The position of the adjacent teeth and the available space for the planned implant restoration were evaluated using digital records and 3D imaging/planning.

The orthodontic phase was directed toward optimizing the mesiodistal, buccolingual, and vertical dimensions of the implant site and establishing an appropriate spatial relationship between the future implant, adjacent roots, and planned prosthetic restoration.

Following completion of orthodontic site optimization, the implant was planned according to the desired prosthetic position.

For Group B, implant placement was planned using the conventional clinical and radiographic approach without the preceding orthodontic optimization protocol.

3D Evaluation of Implant Position

The planned implant position was compared with the postoperative implant position using 3D radiographic/digital assessment. The deviations between the planned and actual implant positions were recorded in millimeters and degrees.

The following parameters were evaluated:

- 3D coronal deviation (mm)
- 3D apical deviation (mm)
- Vertical deviation (mm)
- Mesiodistal deviation (mm)
- Buccolingual deviation (mm)
- Angular deviation (degrees)

The deviations were calculated by superimposing the postoperative implant position on the original treatment plan. Smaller discrepancies indicated greater accuracy of implant placement.

Predefined accuracy thresholds were also used for categorical analysis. An angular deviation of $\leq 3^\circ$ and positional deviations of ≤ 1 mm were considered within the predefined accuracy limits. The proportion of implants satisfying each individual criterion and all predefined criteria simultaneously was calculated.

Assessment of Peri-Implant Tissue Health

Peri-implant tissue health was evaluated at the 6-month follow-up. Clinical assessment included the following parameters:

- Modified plaque index
- Bleeding on probing
- Probing depth
- Width of keratinized mucosa
- Peri-implant mucosal thickness
- Peri-implant suppuration

Probing depth was measured around the implant using a periodontal probe at standardized sites. Bleeding on probing was recorded as present or absent according to the clinical response following probing.

The width of keratinized mucosa was measured in millimeters. Peri-implant mucosal thickness was assessed at the implant site and recorded in millimeters. The presence of suppuration was documented when purulent exudate was detected during clinical examination.

Prosthetic Esthetic Assessment

Prosthetic and peri-implant esthetic outcomes were assessed at the 6-month follow-up using the PES and WES.

The PES was used to evaluate the peri-implant soft-tissue esthetic characteristics, whereas the WES was used to assess the visible prosthetic components. The individual scores were combined to obtain the PES + WES value.

For categorical analysis, a PES ≥ 12 was considered a predefined favorable soft-tissue esthetic outcome. A combined PES/WES score ≥ 18 was used as a predefined criterion for an acceptable overall implant-supported esthetic result.

Radiographic Assessment of Marginal Bone Changes

Marginal bone levels were evaluated radiographically at the 6-month follow-up. Standardized radiographic measurements were obtained at the mesial and distal aspects of each implant.

Marginal bone change was recorded in millimeters, and the mean of the mesial and distal measurements was calculated to represent the overall marginal bone change for each implant. The same radiographic assessment protocol was applied to both groups.

Implant Survival and Complications

Implant survival was assessed at the 6-month follow-up. An implant was considered surviving when it remained functional and clinically stable at the time of assessment.

Biological and prosthetic complications were recorded throughout the follow-up period. These included:

- Peri-implant mucositis
- Prosthetic screw loosening
- Requirement for prosthetic esthetic correction
- Major biological complications

The occurrence of each complication was recorded as a categorical outcome and compared between the two groups.

Correlation Analysis

Correlation analysis was performed to investigate the relationship between 3D implant-position accuracy and peri-implant tissue and esthetic outcomes.

The primary associations assessed included:

- Angular deviation versus PES
- 3D coronal deviation versus PES
- Buccolingual deviation versus mucosal thickness
- Mucosal thickness versus PES
- Probing depth versus PES

Correlation coefficients were calculated to determine the direction and strength of the associations. Negative coefficients indicated an inverse relationship, whereas positive coefficients indicated a direct relationship.

Multivariable Analysis

A multivariable linear regression analysis was performed with PES as the dependent variable to identify factors independently associated with peri-implant esthetic outcomes.

The explanatory variables included:

- 3D orthodontic optimization
- Angular deviation
- Buccolingual deviation
- Mucosal thickness
- Probing depth

Regression coefficients (β), 95% confidence intervals (CI), and corresponding p-values were reported. The analysis was performed to determine whether the relationship between 3D orthodontic optimization and PES remained significant after adjustment for implant-position and peri-implant tissue parameters.

Outcome Measures

The primary outcomes were 3D implant-position accuracy and prosthetic esthetic outcomes, particularly PES.

The secondary outcomes included peri-implant tissue health, mucosal thickness, probing depth, keratinized mucosal width, marginal bone changes, implant survival, and biological or prosthetic complications.

All clinical, radiographic, and esthetic assessments were performed using the same predefined assessment protocol for both treatment groups to facilitate standardized comparison.

Statistical Analysis

The data from the present prospective clinical study were analyzed using Statistical Package for the Social Sciences IBM SPSS Statistics, version 29.0. Continuous variables were expressed as mean $\pm$ standard deviation (SD), while categorical variables were presented as frequency and percentage. The distribution of continuous variables was assessed using the Shapiro–Wilk test for normality. Baseline demographic and clinical characteristics were compared between Group A (3D Orthodontic Optimization Group, n=20) and Group B (Conventional Implant Planning Group, n=20). For normally distributed continuous variables, the independent-samples t-test was used for intergroup comparisons, while the Mann–Whitney U test was applied when the normality assumption was not satisfied. Categorical variables such as sex, implant site, achievement of predefined accuracy criteria, implant survival, mucositis, and prosthetic complications were compared using the Chi-square test or Fisher's exact test, as appropriate. The study compared multiple continuous implant-position parameters, including coronal, apical, vertical, mesiodistal, and buccolingual deviations and angular deviation between the two groups. Peri-implant clinical parameters, marginal bone changes, Pink Esthetic Score (PES), White Esthetic Score (WES), and combined PES+WES scores were similarly compared between groups.

For associations between implant-position accuracy and peri-implant tissue or esthetic outcomes,

Pearson's correlation coefficient (r) was used for normally distributed continuous variables. Correlations were assessed between angular deviation, coronal deviation, buccolingual deviation, mucosal thickness, probing depth, and PES. A multiple linear regression analysis was performed with PES as the dependent variable to identify independent predictors of esthetic outcome. The explanatory variables included 3D orthodontic optimization, angular deviation, buccolingual deviation, mucosal thickness, and probing depth. Regression coefficients (β), 95% CI, and p-values were reported.

All statistical tests were two-tailed, and a p-value <0.05 was considered statistically significant. For categorical outcomes with small expected frequencies, Fisher's exact test was preferred over the Chi-square test. The results were presented with appropriate measures of central tendency and dispersion, together with p-values and effect estimates wherever applicable.

Results

Table 1 & Figure 1 summarize the demographic and baseline clinical characteristics of the 40 patients included in the study. Twenty patients were assigned

to each group: Group A underwent 3D orthodontic optimization, while Group B received conventional implant planning. The mean age was 28.6 ± 5.4 years in Group A and 29.4 ± 5.8 years in Group B, with an overall mean age of 29.0 ± 5.6 years. Group A included 11 males (55.0%) and 9 females (45.0%), whereas Group B comprised 10 males (50.0%) and 10 females (50.0%).

The maxillary central incisor was the most frequently represented implant site in both groups, accounting for 12 cases (60.0%) in Group A and 11 cases (55.0%) in Group B. Maxillary lateral incisor sites were observed in 6 patients (30.0%) in Group A and 7 patients (35.0%) in Group B. Maxillary canine sites accounted for 2 cases (10.0%) in each group. The mean baseline implant-site width was 6.42 ± 0.71 mm in Group A and 6.35 ± 0.76 mm in Group B, with an overall mean of 6.39 ± 0.73 mm.

The two groups demonstrated similar demographic characteristics, implant-site distribution, and baseline implant-site dimensions. This indicates satisfactory baseline comparability between the groups before implementation of the respective treatment approaches and provides an appropriate basis for subsequent comparison of clinical outcomes.

Table 1: Study Population and Baseline Characteristics

Characteristic	Group A (n=20)	Group B (n=20)	Total (n=40)
Age (years), Mean $\pm$ SD	28.6 ± 5.4	29.4 ± 5.8	29.0 ± 5.6
Male, n (%)	11 (55.0)	10 (50.0)	21 (52.5)
Female, n (%)	9 (45.0)	10 (50.0)	19 (47.5)
Maxillary central incisor site, n (%)	12 (60.0)	11 (55.0)	23 (57.5)
Maxillary lateral incisor site, n (%)	6 (30.0)	7 (35.0)	13 (32.5)
Maxillary canine site, n (%)	2 (10.0)	2 (10.0)	4 (10.0)
Baseline implant-site width (mm), Mean $\pm$ SD	6.42 ± 0.71	6.35 ± 0.76	6.39 ± 0.73

Group A – 3D Orthodontic Optimization Group (n = 20), Group B – Conventional Implant Planning Group (n = 20)

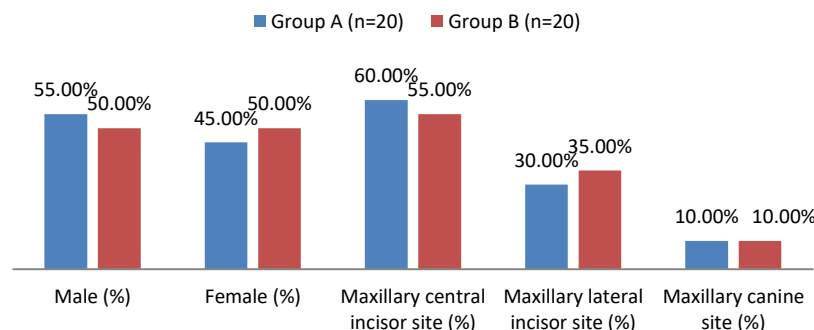


Figure 1: Distribution of Participants According to Group, Sex, and Implant Site

Table 2 & Figure 2 compare the accuracy of 3D implant positioning between Group A (3D Orthodontic Optimization Group) and Group B (Conventional Implant Planning Group). The mean coronal 3D deviation was significantly smaller in Group A (0.82 ± 0.34 mm) than in Group B (1.46 ± 0.62 mm), with a mean difference of -0.64 mm ($p < 0.001$). Similarly, the mean apical 3D deviation was 0.94 ± 0.41 mm in Group A compared with 1.71 ± 0.73 mm in Group B, corresponding to a significant mean difference of -0.77 mm ($p < 0.001$).

A significantly lower vertical deviation was observed in Group A (0.61 ± 0.28 mm) compared with Group B (1.12 ± 0.49 mm), with a mean difference of -0.51 mm ($p < 0.001$). For mesiodistal deviation, the mean value was 0.53 ± 0.24 mm in Group A and 0.91 ± 0.43 mm in Group B, yielding a statistically significant difference of -0.38 mm ($p = 0.002$). The mean buccolingual deviation was also significantly lower in Group A (0.49 ± 0.22 mm) than in Group B (0.88 ± 0.39 mm), with a mean difference of -0.39 mm ($p = 0.001$).

Table 2: Accuracy of 3D Implant Position in both the Groups

Parameter	Group A 3D optimized	Group B Conventional	Mean difference	p-value
Coronal 3D deviation (mm)	0.82 ± 0.34	1.46 ± 0.62	-0.64	<0.001
Apical 3D deviation (mm)	0.94 ± 0.41	1.71 ± 0.73	-0.77	<0.001
Vertical deviation (mm)	0.61 ± 0.28	1.12 ± 0.49	-0.51	<0.001
Mesiodistal deviation (mm)	0.53 ± 0.24	0.91 ± 0.43	-0.38	0.002
Buccolingual deviation (mm)	0.49 ± 0.22	0.88 ± 0.39	-0.39	0.001
Angular deviation (degrees)	2.10 ± 0.91	4.30 ± 1.51	-2.20	<0.001

Group A – 3D Orthodontic Optimization Group (n = 20), Group B – Conventional Implant Planning Group (n = 20)

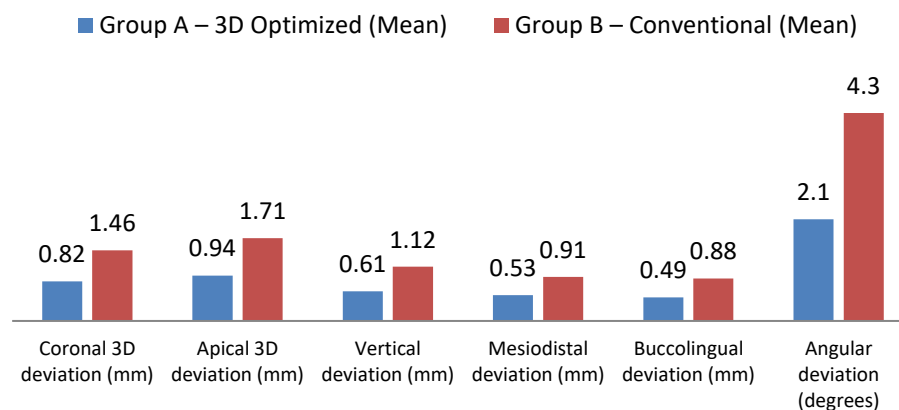


Table 2: Comparison of 3D Implant Positioning Accuracy Between the Study Groups

Table 3 & Figure 3 present the proportion of implants that satisfied the predefined criteria for positional accuracy in Group A (3D Orthodontic Optimization Group) and Group B (Conventional Implant Planning Group). For angular accuracy, 17 implants (85.0%) in Group A achieved a deviation of $\leq 3^\circ$, compared with 8 implants (40.0%) in Group B. This difference was statistically significant ($p < 0.001$). A coronal deviation of ≤ 1 mm was recorded in 17 cases (85.0%) in Group A, whereas 10 cases (50.0%) in Group B met this criterion ($p = 0.018$). Similarly, an apical deviation of ≤ 1 mm was achieved in 15 implants (75.0%) in Group A compared with 7

implants (35.0%) in Group B, with a statistically significant difference between the groups ($p = 0.012$). For vertical positioning, 18 cases (90.0%) in Group A satisfied the ≤ 1 mm accuracy threshold, compared with 12 cases (60.0%) in Group B ($p = 0.028$). When all predefined accuracy parameters were considered collectively, 13 patients (65.0%) in Group A met all the specified criteria, compared with 5 patients (25.0%) in Group B. The difference between the groups was statistically significant ($p = 0.011$). Overall, the 3D Orthodontic Optimization Group demonstrated a significantly higher proportion of cases meeting the predefined criteria for implant-positioning accuracy than the Conventional Implant

Planning Group. These findings suggest that orthodontic optimization of the implant site may

improve the predictability of achieving the planned 3D implant position.

Table 3: Achievement of the Planned Implant Position in Both the Groups

Accuracy category	Group A 3D optimized n (%)	Group B Conventional n(%)	p-value
Angular deviation $\leq 3^\circ$	17 (85.0)	8 (40.0)	<0.001
Coronal deviation ≤ 1 mm	17 (85.0)	10 (50.0)	0.018
Apical deviation ≤ 1 mm	15 (75.0)	7 (35.0)	0.012
Vertical deviation ≤ 1 mm	18 (90.0)	12 (60.0)	0.028
All predefined accuracy criteria achieved	13 (65.0)	5 (25.0)	0.011

Group A – 3D Orthodontic Optimization Group (n = 20), Group B – Conventional Implant Planning Group (n = 20)

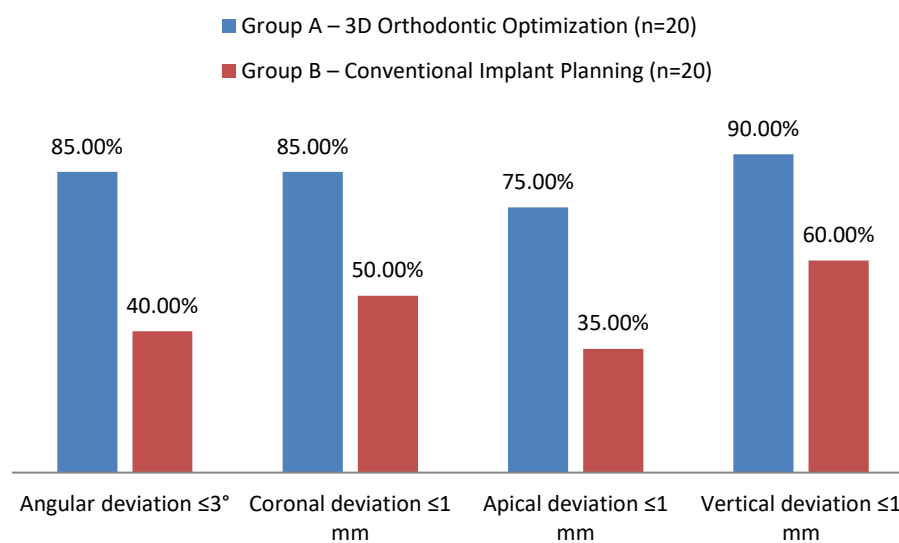


Figure 3: Proportion of Implants Meeting Predefined 3D Positioning Accuracy Criteria

Table 4 & Figure 4 compare the peri-implant tissue health parameters recorded at the 6-month follow-up in Group A (3D Orthodontic Optimization Group) and Group B (Conventional Implant Planning Group). The mean modified plaque index was significantly lower in Group A (0.38 ± 0.17) than in Group B (0.55 ± 0.21), with a statistically significant difference ($p=0.006$).

Bleeding on probing was detected in 3 cases (15.0%) in Group A compared with 8 cases (40.0%) in Group B. Although bleeding occurred less frequently in the 3D Orthodontic Optimization Group, the intergroup difference did not reach statistical significance ($p=0.077$).

The mean probing depth was significantly reduced in Group A (1.88 ± 0.36 mm) compared with Group B (2.34 ± 0.48 mm), with a statistically significant difference ($p=0.002$). The mean width of keratinized

mucosa was significantly greater in Group A (3.42 ± 0.71 mm) than in Group B (2.91 ± 0.64 mm) ($p=0.023$). Likewise, mucosal thickness was significantly higher in Group A (2.15 ± 0.43 mm) compared with Group B (1.74 ± 0.38 mm), with a statistically significant difference ($p=0.004$).

No cases of peri-implant suppuration were recorded in Group A, whereas 1 case (5.0%) was identified in Group B. However, this difference was not statistically significant ($p=1.000$).

Overall, Group A demonstrated more favorable peri-implant tissue findings at 6 months, particularly in relation to plaque accumulation, probing depth, keratinized mucosal width, and mucosal thickness. Although bleeding on probing and suppuration were less frequently observed in Group A, the differences for these parameters were not statistically significant.

Table 4: Peri-Implant Tissue Health at 6 Months in Both the Groups

Clinical parameter	Group A 3D optimized	Group B Conventional	p-value
Modified plaque index	0.38 ± 0.17	0.55 ± 0.21	0.006
Bleeding on probing, n (%)	3 (15.0)	8 (40.0)	0.077
Probing depth (mm)	1.88 ± 0.36	2.34 ± 0.48	0.002
Keratinized mucosa width (mm)	3.42 ± 0.71	2.91 ± 0.64	0.023
Mucosal thickness (mm)	2.15 ± 0.43	1.74 ± 0.38	0.004
Peri-implant suppuration, n (%)	0 (0.0)	1 (5.0)	1.000

Group A – 3D Orthodontic Optimization Group (n = 20), Group B – Conventional Implant Planning Group (n = 20)

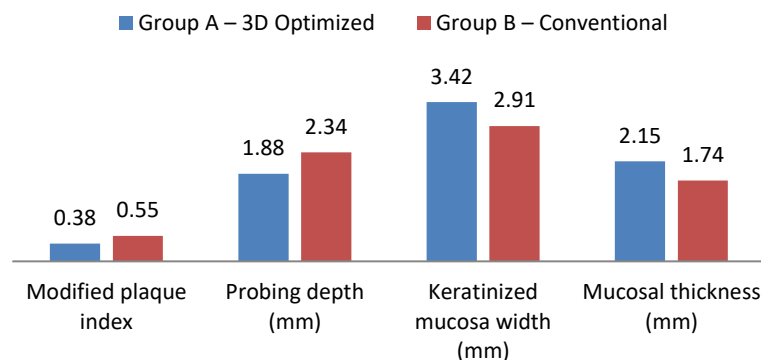
**Figure 4: Comparison of Peri-Implant Tissue Health Parameters at 6 Months Between the Study Groups**

Table 5 & Figure 5 summarize the prosthetic esthetic outcomes observed in Group A (3D Orthodontic Optimization Group) and Group B (Conventional Implant Planning Group). The mean PES was significantly higher in Group A (12.90 ± 1.62) than in Group B (10.80 ± 1.78), with an intergroup difference of 2.10 points ($p < 0.001$). Similarly, the mean WES was significantly greater in Group A (8.20 ± 1.08) compared with Group B (7.10 ± 1.22), yielding a mean difference of 1.10 points ($p = 0.005$). The combined PES + WES score was also significantly higher following 3D orthodontic optimization, with mean values of 21.10 ± 2.05 in Group A and 17.90 ± 2.31 in Group B. The observed difference of 3.20 points was statistically significant ($p < 0.001$). When the predefined esthetic criterion of PES ≥ 12 was applied, 16 patients

(80.0%) in Group A met the threshold compared with 8 patients (40.0%) in Group B, demonstrating a statistically significant difference ($p = 0.011$).

A combined PES/WES score of ≥ 18 was achieved by 18 patients (90.0%) in Group A, whereas only 11 patients (55.0%) in Group B reached this criterion. The difference between the groups was statistically significant ($p = 0.018$).

Overall, the 3D Orthodontic Optimization Group demonstrated significantly more favorable prosthetic esthetic outcomes than the Conventional Implant Planning Group. The higher PES, WES, and combined PES + WES values, together with the greater proportion of patients meeting the predefined esthetic thresholds, indicate improved peri-implant soft-tissue and prosthetic esthetic results following 3D orthodontic site optimization.

Table 5: Prosthetic Esthetic Outcomes in Both the Groups

Esthetic parameter	Group A 3D optimized	Group B Conventional	Mean difference	p-value
PES	12.90 ± 1.62	10.80 ± 1.78	2.10	<0.001
WES	8.20 ± 1.08	7.10 ± 1.22	1.10	0.005
PES + WES	21.10 ± 2.05	17.90 ± 2.31	3.20	<0.001
PES ≥ 12 , n (%)	16 (80.0)	8 (40.0)	—	0.011
PES/WES ≥ 18 , n (%)	18 (90.0)	11 (55.0)	—	0.018

Group A – 3D Orthodontic Optimization Group (n = 20), Group B – Conventional Implant Planning Group (n = 20)

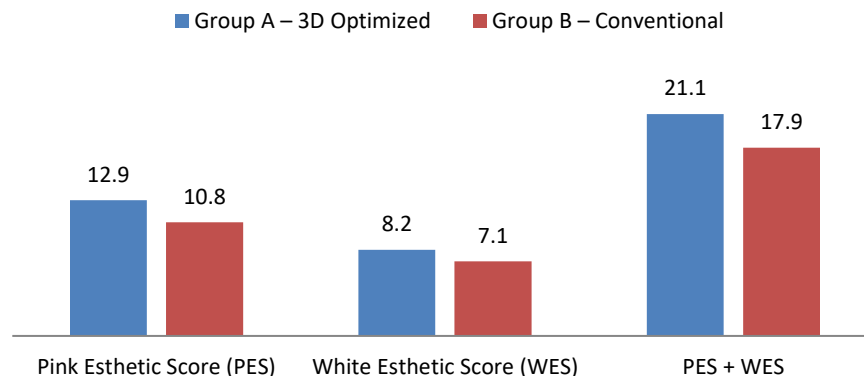


Figure 5: Comparison of Prosthetic Esthetic Scores and Achievement of Predefined Esthetic Thresholds Between the Study Groups

Table 6 & Figure 6 present the comparison of marginal bone loss measured at 6 months in Group A (3D Orthodontic Optimization Group) and Group B (Conventional Implant Planning Group). The mean mesial marginal bone loss was 0.28 ± 0.18 mm in Group A, compared with 0.44 ± 0.25 mm in Group B, and the difference was statistically significant ($p=0.021$). This finding indicates a lower degree of mesial crestal bone remodeling in the 3D Orthodontic Optimization Group.

At the distal aspect, the mean marginal bone loss was also lower in Group A (0.30 ± 0.19 mm) than in Group B (0.47 ± 0.27 mm), with a statistically significant intergroup difference ($p=0.019$). When

the mesial and distal measurements were considered together, the mean marginal bone loss was 0.29 ± 0.17 mm in Group A and 0.46 ± 0.24 mm in Group B. The difference between the groups was statistically significant ($p=0.008$).

Overall, Group A demonstrated significantly less marginal bone loss at both the mesial and distal implant surfaces compared with Group B. These findings suggest that improved implant positioning following 3D orthodontic site optimization may be associated with a more favorable peri-implant hard-tissue response during the initial 6-month healing and follow-up period.

Table 6: Marginal Bone Level Changes at 6 Months in both the Groups

Radiographic parameter	Group A 3D optimized	Group B Conventional	p-value
Mesial marginal bone change (mm)	0.28 ± 0.18	0.44 ± 0.25	0.021
Distal marginal bone change (mm)	0.30 ± 0.19	0.47 ± 0.27	0.019
Mean marginal bone change (mm)	0.29 ± 0.17	0.46 ± 0.24	0.008

Group A – 3D Orthodontic Optimization Group (n = 20), Group B – Conventional Implant Planning Group (n = 20)

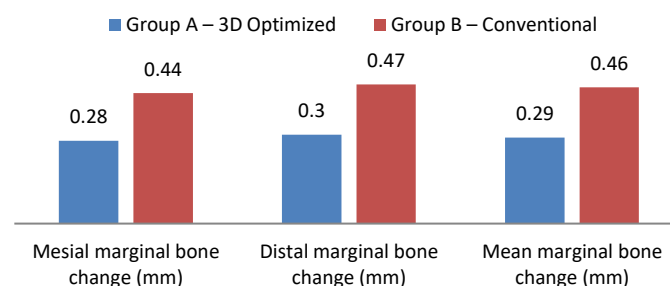


Figure 6: Comparison of Mesial, Distal, and Overall Marginal Bone Loss at 6 Months Between the Study Groups

Table 7 & Figure 7 compare implant survival and the occurrence of biological and prosthetic complications at the 6-month follow-up in Group A (3D Orthodontic Optimization Group) and Group B (Conventional Implant Planning Group). All 20 implants in Group A remained functional at 6 months, corresponding to a survival rate of 100.0% (20/20), whereas 19 of 20 implants in Group B survived, resulting in a survival rate of 95.0%. Although survival was numerically higher in Group A, the difference between the groups was not statistically significant ($p=1.000$).

Peri-implant mucositis was identified in 2 patients (10.0%) in Group A compared with 5 patients (25.0%) in Group B. Although the occurrence was lower following 3D orthodontic optimization, the difference was not statistically significant ($p=0.407$). Prosthetic screw loosening was recorded in 1 case (5.0%) in Group A and 2 cases (10.0%) in Group B, with no statistically significant intergroup difference ($p=1.000$).

The need for prosthetic esthetic correction was observed in 1 patient (5.0%) in Group A and 5 patients (25.0%) in Group B. Despite the lower frequency in the 3D Orthodontic Optimization Group, this difference did not reach statistical significance ($p=0.182$). Major biological complications were not recorded in Group A, while 1 patient (5.0%) in Group B experienced a major biological complication. This difference was also not statistically significant ($p=1.000$).

Overall, Group A showed a numerically more favorable profile with respect to implant survival and postoperative complications. Higher implant survival and lower frequencies of peri-implant mucositis, prosthetic screw loosening, esthetic correction, and major biological complications were observed in the 3D Orthodontic Optimization Group. However, none of these categorical outcomes demonstrated a statistically significant difference between the groups at the 6-month assessment.

Table 7: Implant Survival and Biological/Prosthetic Complications in both the Groups

Outcome	Group A n (%)	Group B n (%)	p-value
Implant survival at 6 months	20 (100.0)	19 (95.0)	1.000
Peri-implant mucositis	2 (10.0)	5 (25.0)	0.407
Prosthetic screw loosening	1 (5.0)	2 (10.0)	1.000
Prosthetic esthetic correction required	1 (5.0)	5 (25.0)	0.182
Major biological complication	0 (0.0)	1 (5.0)	1.000

Group A – 3D Orthodontic Optimization Group (n = 20), Group B – Conventional Implant Planning Group (n = 20)

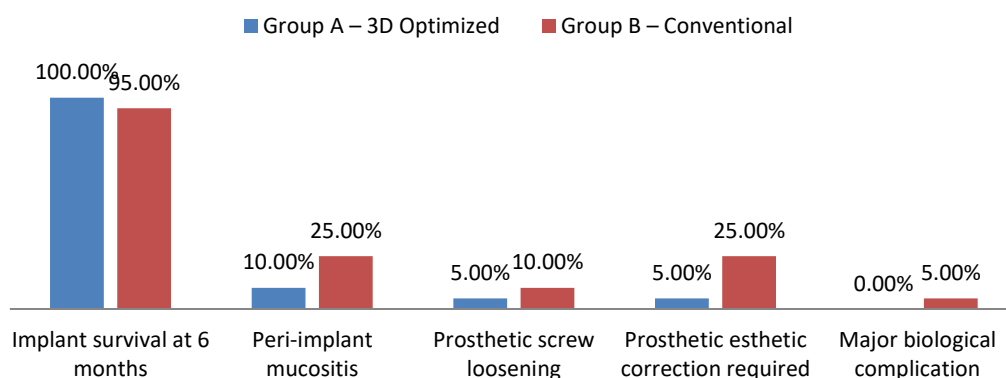


Figure 7: Comparison of Implant Survival and Biological and Prosthetic Complications at 6 Months

Table 8 presents the associations between 3D implant positioning accuracy and peri-implant esthetic and soft-tissue parameters. A significant moderate-to-strong negative correlation was identified between angular deviation and PES ($r =$

-0.62 , $p < 0.001$). This finding indicates that implants positioned with greater angular discrepancies from the planned orientation were associated with less favorable esthetic outcomes. Likewise, 3D coronal deviation was negatively

correlated with PES ($r = -0.54$, $p < 0.001$), demonstrating that greater deviations in the coronal position were associated with lower esthetic scores.

A significant moderate inverse relationship was observed between buccolingual implant deviation and peri-implant mucosal thickness ($r = -0.48$, $p = 0.002$). Thus, increased displacement of the implant in the buccolingual direction was associated with thinner peri-implant mucosal tissues. In contrast, mucosal thickness showed a significant positive correlation with PES ($r = 0.56$, $p < 0.001$), indicating that patients with greater peri-implant soft-tissue thickness generally exhibited better esthetic outcomes.

Additionally, probing depth demonstrated a significant moderate negative association with PES ($r = -0.43$, $p = 0.006$), suggesting that greater probing depths were related to less favorable peri-implant esthetic scores.

Overall, the findings indicate that closer adherence to the planned 3D implant position was associated with improved peri-implant soft-tissue characteristics and superior esthetic outcomes. In particular, lower positional deviations, adequate mucosal thickness, and favorable probing-depth measurements were associated with higher PES values, highlighting the importance of precise implant placement for achieving optimal prosthetic esthetics.

Table 8: Correlation Between Implant Position Accuracy and Esthetic/Tissue Outcomes

Association	Correlation coefficient (r)	p-value	Interpretation
Angular deviation vs PES	-0.62	<0.001	Moderate-to-strong inverse correlation
3D coronal deviation vs PES	-0.54	<0.001	Moderate inverse correlation
Buccolingual deviation vs mucosal thickness	-0.48	0.002	Moderate inverse correlation
Mucosal thickness vs PES	0.56	<0.001	Moderate positive correlation
Probing depth vs PES	-0.43	0.006	Moderate inverse correlation

Table 9 presents the multivariable linear regression analysis conducted to determine the independent factors associated with the PES. After adjustment for other clinical and implant-position parameters, 3D orthodontic optimization remained a significant positive predictor of PES ($\beta = +1.21$; 95% CI: 0.42–2.00; $p = 0.004$). This finding indicates that patients who underwent 3D orthodontic optimization achieved higher esthetic scores independent of the other variables included in the model.

Angular deviation showed a significant inverse association with PES ($\beta = -0.31$; 95% CI: -0.50 to -0.12; $p = 0.002$). Specifically, each 1° increase in angular deviation was associated with an estimated 0.31-point reduction in PES, after controlling for the remaining covariates. Buccolingual deviation was also negatively associated with PES ($\beta = -0.88$; 95% CI: -1.52 to -0.24; $p = 0.009$), demonstrating that greater displacement in the buccolingual direction was associated with less favorable esthetic outcomes.

Conversely, mucosal thickness was positively associated with PES ($\beta = +1.36$; 95% CI: 0.52–2.20; $p = 0.002$). Thus, a 1-mm increase in peri-implant mucosal thickness corresponded to an estimated 1.36-point increase in PES, independent of the other factors in the regression model. Probing depth demonstrated a significant negative relationship with PES ($\beta = -0.74$; 95% CI: -1.39 to -0.09; $p = 0.027$), indicating that greater probing depths were associated with lower esthetic scores.

Overall, the regression analysis identified 3D orthodontic optimization and greater peri-implant mucosal thickness as independent factors associated with better esthetic outcomes, whereas increased angular deviation, buccolingual deviation, and probing depth were independently associated with lower PES values. These findings highlight the importance of precise 3D implant positioning and adequate peri-implant soft-tissue characteristics in achieving favorable peri-implant esthetic results.

Table 9: Multivariable Analysis to identify independent predictors of the PES

Predictor	β coefficient	95% CI	p-value
3D orthodontic optimization	+1.21	0.42 to 2.00	0.004
Angular deviation (per 1°)	-0.31	-0.50 to -0.12	0.002
Buccolingual deviation (per 1 mm)	-0.88	-1.52 to -0.24	0.009
Mucosal thickness (per 1 mm)	+1.36	0.52 to 2.20	0.002
Probing depth (per 1 mm)	-0.74	-1.39 to -0.09	0.027

Results

Table 1 & Figure 1 summarize the demographic and baseline clinical characteristics of the 40 patients included in the study. Twenty patients were assigned to each group: Group A underwent 3D orthodontic optimization, while Group B received conventional implant planning. The mean age was 28.6 ± 5.4 years in Group A and 29.4 ± 5.8 years in Group B, with an overall mean age of 29.0 ± 5.6 years. Group A included 11 males (55.0%) and 9 females (45.0%), whereas Group B comprised 10 males (50.0%) and 10 females (50.0%).

The maxillary central incisor was the most frequently represented implant site in both groups, accounting for subsequent comparison of clinical outcomes.

for 12 cases (60.0%) in Group A and 11 cases (55.0%) in Group B. Maxillary lateral incisor sites were observed in 6 patients (30.0%) in Group A and 7 patients (35.0%) in Group B. Maxillary canine sites accounted for 2 cases (10.0%) in each group. The mean baseline implant-site width was 6.42 ± 0.71 mm in Group A and 6.35 ± 0.76 mm in Group B, with an overall mean of 6.39 ± 0.73 mm.

The two groups demonstrated similar demographic characteristics, implant-site distribution, and baseline implant-site dimensions. This indicates satisfactory baseline comparability between the groups before implementation of the respective treatment approaches and provides an appropriate basis

Table 1: Study Population and Baseline Characteristics

Characteristic	Group A (n=20)	Group B (n=20)	Total (n=40)
Age (years), Mean $\pm$ SD	28.6 ± 5.4	29.4 ± 5.8	29.0 ± 5.6
Male, n (%)	11 (55.0)	10 (50.0)	21 (52.5)
Female, n (%)	9 (45.0)	10 (50.0)	19 (47.5)
Maxillary central incisor site, n (%)	12 (60.0)	11 (55.0)	23 (57.5)
Maxillary lateral incisor site, n (%)	6 (30.0)	7 (35.0)	13 (32.5)
Maxillary canine site, n (%)	2 (10.0)	2 (10.0)	4 (10.0)
Baseline implant-site width (mm), Mean $\pm$ SD	6.42 ± 0.71	6.35 ± 0.76	6.39 ± 0.73

Group A – 3D Orthodontic Optimization Group (n = 20), Group B – Conventional Implant Planning Group (n = 20)

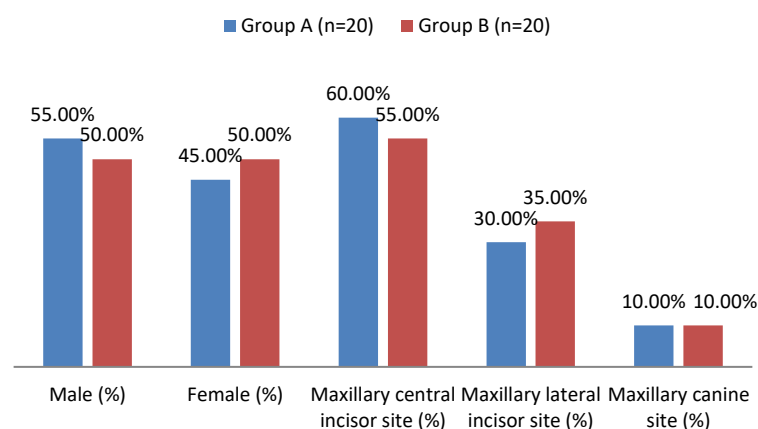
**Figure 1: Distribution of Participants According to Group, Sex, and Implant Site**

Table 2 & Figure 2 compare the accuracy of 3D implant positioning between Group A (3D Orthodontic Optimization Group) and Group B (Conventional Implant Planning Group). The mean coronal 3D deviation was significantly smaller in Group A (0.82 ± 0.34 mm) than in Group B (1.46 ± 0.62 mm), with a mean difference of -0.64 mm ($p < 0.001$). Similarly, the mean apical 3D deviation was 0.94 ± 0.41 mm in Group A compared with 1.71 ± 0.73 mm in Group B, corresponding to a significant mean difference of -0.77 mm ($p < 0.001$).

A significantly lower vertical deviation was observed in Group A (0.61 ± 0.28 mm) compared with Group B (1.12 ± 0.49 mm), with a mean difference of -0.51 mm ($p < 0.001$). For mesiodistal deviation, the mean value was 0.53 ± 0.24 mm in Group A and 0.91 ± 0.43 mm in Group B, yielding a statistically significant difference of -0.38 mm ($p = 0.002$). The mean buccolingual deviation was also significantly lower in Group A (0.49 ± 0.22 mm) than in Group B (0.88 ± 0.39 mm), with a mean difference of -0.39 mm ($p = 0.001$).

Table 2: Accuracy of 3D Implant Position in both the Groups

Parameter	Group A 3D optimized	Group B Conventional	Mean difference	p-value
Coronal 3D deviation (mm)	0.82 ± 0.34	1.46 ± 0.62	-0.64	<0.001
Apical 3D deviation (mm)	0.94 ± 0.41	1.71 ± 0.73	-0.77	<0.001
Vertical deviation (mm)	0.61 ± 0.28	1.12 ± 0.49	-0.51	<0.001
Mesiodistal deviation (mm)	0.53 ± 0.24	0.91 ± 0.43	-0.38	0.002
Buccolingual deviation (mm)	0.49 ± 0.22	0.88 ± 0.39	-0.39	0.001
Angular deviation (degrees)	2.10 ± 0.91	4.30 ± 1.51	-2.20	<0.001

Group A – 3D Orthodontic Optimization Group (n = 20), Group B – Conventional Implant Planning Group (n = 20)

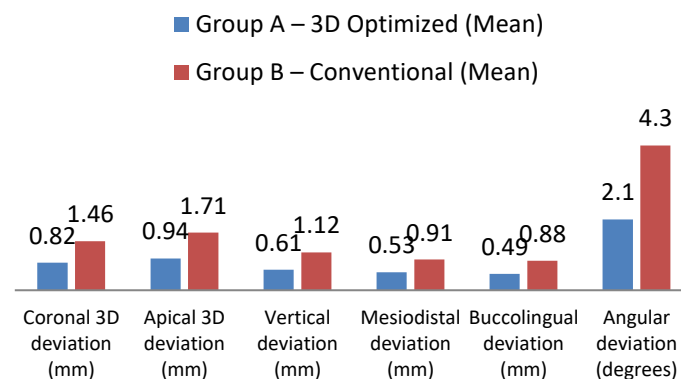


Table 2: Comparison of 3D Implant Positioning Accuracy Between the Study Groups

Table 3 & Figure 3 present the proportion of implants that satisfied the predefined criteria for positional accuracy in Group A (3D Orthodontic Optimization Group) and Group B (Conventional Implant Planning Group). For angular accuracy, 17 implants (85.0%) in Group A achieved a deviation of $\leq 3^\circ$, compared with 8 implants (40.0%) in Group B. This difference was statistically significant ($p < 0.001$). A coronal deviation of ≤ 1 mm was recorded in 17 cases (85.0%) in Group A, whereas 10 cases (50.0%) in Group B met this criterion ($p = 0.018$). Similarly, an apical deviation of ≤ 1 mm was achieved in 15 implants (75.0%) in Group A compared with 7

implants (35.0%) in Group B, with a statistically significant difference between the groups ($p = 0.012$). For vertical positioning, 18 cases (90.0%) in Group A satisfied the ≤ 1 mm accuracy threshold, compared with 12 cases (60.0%) in Group B ($p = 0.028$). When all predefined accuracy parameters were considered collectively, 13 patients (65.0%) in Group A met all the specified criteria, compared with 5 patients (25.0%) in Group B. The difference between the groups was statistically significant ($p = 0.011$).

Overall, the 3D Orthodontic Optimization Group demonstrated a significantly higher proportion of cases meeting the predefined criteria for implant-

positioning accuracy than the Conventional Implant Planning Group. These findings suggest that orthodontic optimization of the implant site may

improve the predictability of achieving the planned 3D implant position.

Table 3: Achievement of the Planned Implant Position in Both the Groups

Accuracy category	Group A 3D optimized n (%)	Group B Conventional n(%)	p-value
Angular deviation $\leq 3^\circ$	17 (85.0)	8 (40.0)	<0.001
Coronal deviation ≤ 1 mm	17 (85.0)	10 (50.0)	0.018
Apical deviation ≤ 1 mm	15 (75.0)	7 (35.0)	0.012
Vertical deviation ≤ 1 mm	18 (90.0)	12 (60.0)	0.028
All predefined accuracy criteria achieved	13 (65.0)	5 (25.0)	0.011

Group A – 3D Orthodontic Optimization Group (n = 20), Group B – Conventional Implant Planning Group (n = 20)

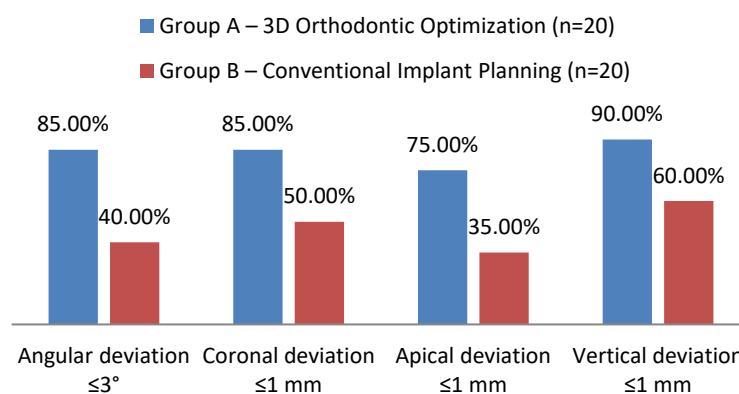


Figure 3: Proportion of Implants Meeting Predefined 3D Positioning Accuracy Criteria

Table 4 & Figure 4 compare the peri-implant tissue health parameters recorded at the 6-month follow-up in Group A (3D Orthodontic Optimization Group) and Group B (Conventional Implant Planning Group). The mean modified plaque index was significantly lower in Group A (0.38 ± 0.17) than in Group B (0.55 ± 0.21), with a statistically significant difference ($p=0.006$).

Bleeding on probing was detected in 3 cases (15.0%) in Group A compared with 8 cases (40.0%) in Group B. Although bleeding occurred less frequently in the 3D Orthodontic Optimization Group, the intergroup difference did not reach statistical significance ($p=0.077$).

The mean probing depth was significantly reduced in Group A (1.88 ± 0.36 mm) compared with Group B (2.34 ± 0.48 mm), with a statistically significant difference ($p=0.002$). The mean width of keratinized

mucosa was significantly greater in Group A (3.42 ± 0.71 mm) than in Group B (2.91 ± 0.64 mm) ($p=0.023$). Likewise, mucosal thickness was significantly higher in Group A (2.15 ± 0.43 mm) compared with Group B (1.74 ± 0.38 mm), with a statistically significant difference ($p=0.004$).

No cases of peri-implant suppuration were recorded in Group A, whereas 1 case (5.0%) was identified in Group B. However, this difference was not statistically significant ($p=1.000$).

Overall, Group A demonstrated more favorable peri-implant tissue findings at 6 months, particularly in relation to plaque accumulation, probing depth, keratinized mucosal width, and mucosal thickness. Although bleeding on probing and suppuration were less frequently observed in Group A, the differences for these parameters were not statistically significant.

Table 4: Peri-Implant Tissue Health at 6 Months in Both the Groups

Clinical parameter	Group A 3D optimized	Group B Conventional	p-value
Modified plaque index	0.38 ± 0.17	0.55 ± 0.21	0.006
Bleeding on probing, n (%)	3 (15.0)	8 (40.0)	0.077

Probing depth (mm)	1.88 ± 0.36	2.34 ± 0.48	0.002
Keratinized mucosa width (mm)	3.42 ± 0.71	2.91 ± 0.64	0.023
Mucosal thickness (mm)	2.15 ± 0.43	1.74 ± 0.38	0.004
Peri-implant suppuration, n (%)	0 (0.0)	1 (5.0)	1.000

Group A – 3D Orthodontic Optimization Group (n = 20), Group B – Conventional Implant Planning Group (n = 20)

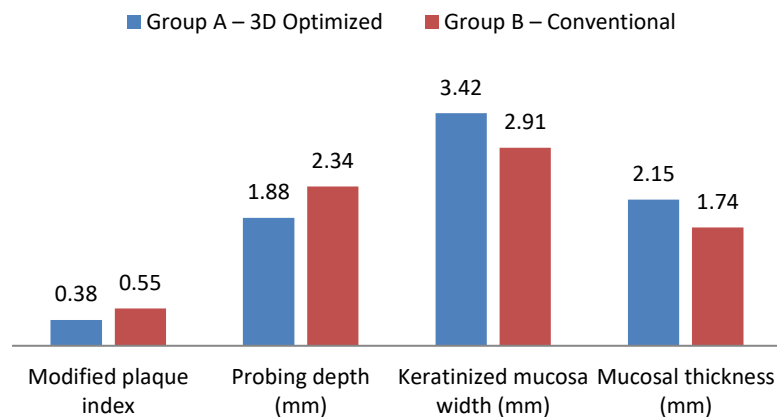


Figure 4: Comparison of Peri-Implant Tissue Health Parameters at 6 Months Between the Study Groups

Table 5 & Figure 5 summarize the prosthetic esthetic outcomes observed in Group A (3D Orthodontic Optimization Group) and Group B (Conventional Implant Planning Group). The mean PES was significantly higher in Group A (12.90 ± 1.62) than in Group B (10.80 ± 1.78), with an intergroup difference of 2.10 points ($p < 0.001$). Similarly, the mean WES was significantly greater in Group A (8.20 ± 1.08) compared with Group B (7.10 ± 1.22), yielding a mean difference of 1.10 points ($p = 0.005$). The combined PES + WES score was also significantly higher following 3D orthodontic optimization, with mean values of 21.10 ± 2.05 in Group A and 17.90 ± 2.31 in Group B. The observed difference of 3.20 points was statistically significant ($p < 0.001$). When the predefined esthetic criterion of PES ≥ 12 was applied, 16 patients

(80.0%) in Group A met the threshold compared with 8 patients (40.0%) in Group B, demonstrating a statistically significant difference ($p = 0.011$).

A combined PES/WES score of ≥ 18 was achieved by 18 patients (90.0%) in Group A, whereas only 11 patients (55.0%) in Group B reached this criterion. The difference between the groups was statistically significant ($p = 0.018$).

Overall, the 3D Orthodontic Optimization Group demonstrated significantly more favorable prosthetic esthetic outcomes than the Conventional Implant Planning Group. The higher PES, WES, and combined PES + WES values, together with the greater proportion of patients meeting the predefined esthetic thresholds, indicate improved peri-implant soft-tissue and prosthetic esthetic results following 3D orthodontic site optimization.

Table 5: Prosthetic Esthetic Outcomes in Both the Groups

Esthetic parameter	Group A 3D optimized	Group B Conventional	Mean difference	p-value
PES	12.90 ± 1.62	10.80 ± 1.78	2.10	<0.001
WES	8.20 ± 1.08	7.10 ± 1.22	1.10	0.005
PES + WES	21.10 ± 2.05	17.90 ± 2.31	3.20	<0.001
PES ≥ 12 , n (%)	16 (80.0)	8 (40.0)	—	0.011
PES/WES ≥ 18 , n (%)	18 (90.0)	11 (55.0)	—	0.018

Group A – 3D Orthodontic Optimization Group (n = 20), Group B – Conventional Implant Planning Group (n = 20)

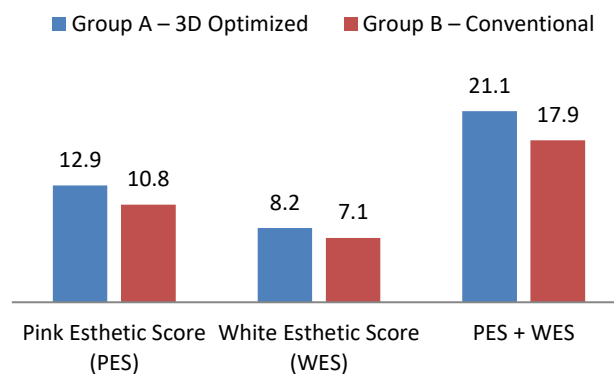


Figure 5: Comparison of Prosthetic Esthetic Scores and Achievement of Predefined Esthetic Thresholds Between the Study Groups

Table 6 & Figure 6 present the comparison of marginal bone loss measured at 6 months in Group A (3D Orthodontic Optimization Group) and Group B (Conventional Implant Planning Group). The mean mesial marginal bone loss was 0.28 ± 0.18 mm in Group A, compared with 0.44 ± 0.25 mm in Group B, and the difference was statistically significant ($p=0.021$). This finding indicates a lower degree of mesial crestal bone remodeling in the 3D Orthodontic Optimization Group.

At the distal aspect, the mean marginal bone loss was also lower in Group A (0.30 ± 0.19 mm) than in Group B (0.47 ± 0.27 mm), with a statistically significant intergroup difference ($p=0.019$). When

the mesial and distal measurements were considered together, the mean marginal bone loss was 0.29 ± 0.17 mm in Group A and 0.46 ± 0.24 mm in Group B. The difference between the groups was statistically significant ($p=0.008$).

Overall, Group A demonstrated significantly less marginal bone loss at both the mesial and distal implant surfaces compared with Group B. These findings suggest that improved implant positioning following 3D orthodontic site optimization may be associated with a more favorable peri-implant hard-tissue response during the initial 6-month healing and follow-up period.

Table 6: Marginal Bone Level Changes at 6 Months in both the Groups

Radiographic parameter	Group A 3D optimized	Group B Conventional	p-value
Mesial marginal bone change (mm)	0.28 ± 0.18	0.44 ± 0.25	0.021
Distal marginal bone change (mm)	0.30 ± 0.19	0.47 ± 0.27	0.019
Mean marginal bone change (mm)	0.29 ± 0.17	0.46 ± 0.24	0.008

Group A – 3D Orthodontic Optimization Group ($n = 20$), Group B – Conventional Implant Planning Group ($n = 20$)

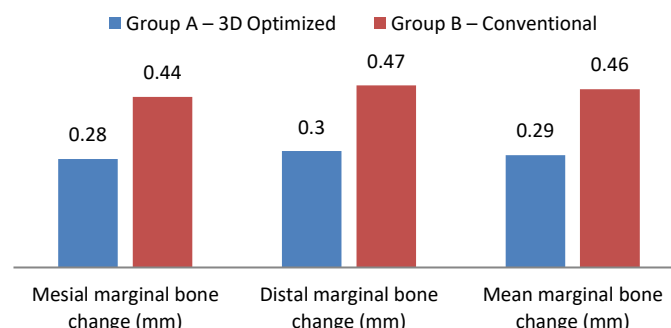


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Table 7 & Figure 7 compare implant survival and the occurrence of biological and prosthetic complications at the 6-month follow-up in Group A (3D Orthodontic Optimization Group) and Group B (Conventional Implant Planning Group). All 20 implants in Group A remained functional at 6 months, corresponding to a survival rate of 100.0% (20/20), whereas 19 of 20 implants in Group B survived, resulting in a survival rate of 95.0%. Although survival was numerically higher in Group A, the difference between the groups was not statistically significant ($p=1.000$).

Peri-implant mucositis was identified in 2 patients (10.0%) in Group A compared with 5 patients (25.0%) in Group B. Although the occurrence was lower following 3D orthodontic optimization, the difference was not statistically significant ($p=0.407$). Prosthetic screw loosening was recorded in 1 case (5.0%) in Group A and 2 cases (10.0%) in Group B, with no statistically significant intergroup difference ($p=1.000$).

The need for prosthetic esthetic correction was observed in 1 patient (5.0%) in Group A and 5 patients (25.0%) in Group B. Despite the lower frequency in the 3D Orthodontic Optimization Group, this difference did not reach statistical significance ($p=0.182$). Major biological complications were not recorded in Group A, while 1 patient (5.0%) in Group B experienced a major biological complication. This difference was also not statistically significant ($p=1.000$).

Overall, Group A showed a numerically more favorable profile with respect to implant survival and postoperative complications. Higher implant survival and lower frequencies of peri-implant mucositis, prosthetic screw loosening, esthetic correction, and major biological complications were observed in the 3D Orthodontic Optimization Group. However, none of these categorical outcomes demonstrated a statistically significant difference between the groups at the 6-month assessment.

Table 7: Implant Survival and Biological/Prosthetic Complications in both the Groups

Outcome	Group A n (%)	Group B n (%)	p-value
Implant survival at 6 months	20 (100.0)	19 (95.0)	1.000
Peri-implant mucositis	2 (10.0)	5 (25.0)	0.407
Prosthetic screw loosening	1 (5.0)	2 (10.0)	1.000
Prosthetic esthetic correction required	1 (5.0)	5 (25.0)	0.182
Major biological complication	0 (0.0)	1 (5.0)	1.000

Group A – 3D Orthodontic Optimization Group (n = 20), Group B – Conventional Implant Planning Group (n = 20)

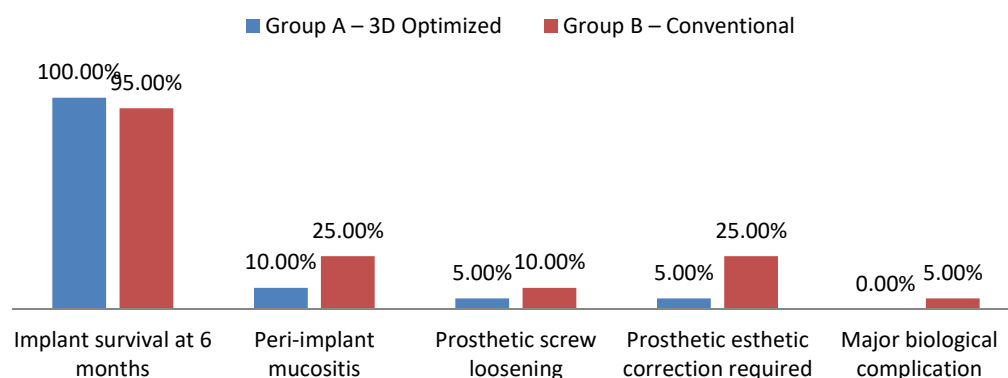


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A significant moderate inverse relationship was observed between buccolingual implant deviation and peri-implant mucosal thickness ($r = -0.48$, $p = 0.002$). Thus, increased displacement of the implant in the buccolingual direction was associated with thinner peri-implant mucosal tissues. In contrast, mucosal thickness showed a significant positive correlation with PES ($r = 0.56$, $p < 0.001$), indicating that patients with greater peri-implant soft-tissue thickness generally exhibited better esthetic outcomes.

Additionally, probing depth demonstrated a significant moderate negative association with PES ($r = -0.43$, $p = 0.006$), suggesting that greater probing depths were related to less favorable peri-implant esthetic scores.

Overall, the findings indicate that closer adherence to the planned 3D implant position was associated with improved peri-implant soft-tissue characteristics and superior esthetic outcomes. In particular, lower positional deviations, adequate mucosal thickness, and favorable probing-depth measurements were associated with higher PES values, highlighting the importance of precise implant placement for achieving optimal prosthetic esthetics.

Table 8: Correlation Between Implant Position Accuracy and Esthetic/Tissue Outcomes

Association	Correlation coefficient (r)	p-value	Interpretation
Angular deviation vs PES	-0.62	<0.001	Moderate-to-strong inverse correlation
3D coronal deviation vs PES	-0.54	<0.001	Moderate inverse correlation
Buccolingual deviation vs mucosal thickness	-0.48	0.002	Moderate inverse correlation
Mucosal thickness vs PES	0.56	<0.001	Moderate positive correlation
Probing depth vs PES	-0.43	0.006	Moderate inverse correlation

Table 9 presents the multivariable linear regression analysis conducted to determine the independent factors associated with the PES. After adjustment for other clinical and implant-position parameters, 3D orthodontic optimization remained a significant positive predictor of PES ($\beta = +1.21$; 95% CI: 0.42–2.00; $p = 0.004$). This finding indicates that patients who underwent 3D orthodontic optimization achieved higher esthetic scores independent of the other variables included in the model.

Angular deviation showed a significant inverse association with PES ($\beta = -0.31$; 95% CI: -0.50 to -0.12; $p = 0.002$). Specifically, each 1° increase in angular deviation was associated with an estimated 0.31-point reduction in PES, after controlling for the remaining covariates. Buccolingual deviation was also negatively associated with PES ($\beta = -0.88$; 95% CI: -1.52 to -0.24; $p = 0.009$), demonstrating that greater displacement in the buccolingual direction was associated with less favorable esthetic outcomes.

Conversely, mucosal thickness was positively associated with PES ($\beta = +1.36$; 95% CI: 0.52–2.20; $p = 0.002$). Thus, a 1-mm increase in peri-implant mucosal thickness corresponded to an estimated 1.36-point increase in PES, independent of the other factors in the regression model. Probing depth demonstrated a significant negative relationship with PES ($\beta = -0.74$; 95% CI: -1.39 to -0.09; $p = 0.027$), indicating that greater probing depths were associated with lower esthetic scores.

Overall, the regression analysis identified 3D orthodontic optimization and greater peri-implant mucosal thickness as independent factors associated with better esthetic outcomes, whereas increased angular deviation, buccolingual deviation, and probing depth were independently associated with lower PES values. These findings highlight the importance of precise 3D implant positioning and adequate peri-implant soft-tissue characteristics in achieving favorable peri-implant esthetic results.

Table 9: Multivariable Analysis to identify independent predictors of the PES

Predictor	β coefficient	95% CI	p-value
3D orthodontic optimization	+1.21	0.42 to 2.00	0.004
Angular deviation (per 1°)	-0.31	-0.50 to -0.12	0.002
Buccolingual deviation (per 1 mm)	-0.88	-1.52 to -0.24	0.009
Mucosal thickness (per 1 mm)	+1.36	0.52 to 2.20	0.002
Probing depth (per 1 mm)	-0.74	-1.39 to -0.09	0.027

Discussion

The present study evaluated the influence of 3D orthodontic optimization of implant sites on implant position, peri-implant tissue health, and prosthetic esthetic outcomes. The findings support the concept that appropriate preparation of the implant site before surgery can improve the spatial conditions required for prosthetically driven implant placement. In particular, orthodontic management of tooth position and root angulation may provide a more favorable environment for implant placement while facilitating subsequent restoration and maintenance of peri-implant tissues.

The role of orthodontic site development has previously been demonstrated by Amato et al. (2012) [10], who investigated orthodontic forced extraction as a method of developing implant sites. Their preliminary study demonstrated that controlled orthodontic tooth movement could contribute to modification of the hard and soft tissue environment at prospective implant sites. These findings are relevant to the present study because orthodontic optimization similarly aims to improve the anatomical conditions before implant placement rather than attempting to compensate for unfavorable site characteristics during surgery. The present findings therefore reinforce the clinical rationale for incorporating orthodontic site preparation into interdisciplinary implant treatment. Peri-implant soft-tissue architecture is an important determinant of esthetic success, particularly in the anterior region. Roccuzzo et al. (2018) [11], in a systematic review, evaluated the relationship between papilla height and the distance from the interproximal bone crest to the contact point. Their findings emphasized the importance of the underlying hard-tissue anatomy and the spatial relationship between the implant restoration and adjacent structures in determining papillary appearance. The present study is consistent with this concept, as optimization of the implant site through orthodontic correction may improve the spatial relationship between adjacent roots and the

prospective implant, thereby creating more favorable conditions for peri-implant soft-tissue preservation.

The importance of the vertical relationship between the interproximal contact point and alveolar bone crest was originally highlighted by Tarnow et al. (1992) [12]. They demonstrated that the likelihood of complete interproximal papilla fill was associated with the distance between the contact point and the underlying bone crest. This observation has substantial relevance to implant esthetics because inadequate papillary fill may result in visible interproximal spaces and compromised soft-tissue harmony. In the context of the present study, 3D orthodontic optimization may help establish more favorable interproximal relationships before implant placement, potentially supporting improved papillary architecture and prosthetic esthetics.

Similarly, Choquet et al. (2001) [13] evaluated papilla levels adjacent to single-tooth implants and demonstrated the importance of the relationship between implant position, adjacent teeth, and the surrounding periodontal structures in determining the final papillary appearance. Their findings reinforce the concept that esthetic implant therapy cannot be evaluated solely on the basis of osseointegration or implant survival. The 3D positioning of the implant relative to neighboring teeth and the available hard- and soft-tissue structures must also be considered. The improved implant positioning observed following orthodontic site optimization in the present study may therefore have contributed to more favorable peri-implant esthetic conditions.

Kawai and Almeida (2008) [14] further evaluated the presence or absence of papilla between teeth and implants and highlighted the multifactorial nature of interproximal soft-tissue formation. Their findings indicate that papillary presence is influenced by anatomical and spatial variables surrounding the implant site. This supports the importance of controlling the local 3D environment before implant placement. In the present study, orthodontic optimization was used to improve tooth position and

available implant space before surgery, thereby potentially reducing unfavorable root proximity and improving the anatomical conditions required for soft-tissue stability.

3D evaluation of peri-implant tissues has also provided important evidence regarding changes in the esthetic zone. Parvini et al. (2022) [15] used prospective 3D volumetric assessment to evaluate peri-implant tissue stability following immediate and delayed implant placement. Their findings demonstrate the value of 3D assessment for detecting volumetric changes that may not be adequately identified through conventional 2D clinical evaluation. The present study similarly emphasizes the importance of 3D assessment because implant position, peri-implant tissue health, and prosthetic esthetics are closely interconnected spatial outcomes.

Taken together above mentioned studies provide a consistent, the findings of scientific basis for considering implant rehabilitation as a multidisciplinary and 3D treatment process. The available evidence indicates that successful esthetic implant therapy depends on appropriate management of the hard- and soft-tissue environment, adequate spatial relationships between implants and adjacent teeth, and careful consideration of the final prosthetic requirements.

The present study extends these concepts by specifically evaluating orthodontic optimization as a preparatory step before implant placement. Rather than treating implant placement as an isolated surgical procedure, the approach used in this study emphasizes modification of the dental and anatomical environment before implant insertion. This may allow the implant to be positioned more accurately within the available restorative envelope and may facilitate improved peri-implant tissue and prosthetic outcomes.

The findings should nevertheless be interpreted within the context of the study design and clinical variables involved. Implant position and peri-implant tissue conditions can be influenced by several factors, including the initial ridge anatomy, periodontal phenotype, surgical technique, implant dimensions, prosthetic design, oral hygiene, and individual healing response. Therefore, the observed relationship between orthodontic site optimization and treatment outcomes should not be attributed exclusively to orthodontic intervention. Longer follow-up and

larger prospective studies may further clarify whether the improvements observed following orthodontic optimization are maintained over time.

Overall, the present findings support the integration of orthodontic site preparation into interdisciplinary implant rehabilitation, particularly when unfavorable tooth position, inadequate spacing, or root angulation may compromise prosthetically driven implant placement. 3D orthodontic optimization may provide a valuable means of improving the anatomical conditions before surgery and, consequently, enhancing the biological and esthetic predictability of implant-supported rehabilitation.

Limitations

The present study has several limitations that should be considered when interpreting the findings. First, the study included a relatively small sample of 40 patients, with only 20 participants in each treatment group. Although statistically significant differences were identified for several outcomes, the limited sample size may reduce the statistical power for detecting smaller differences, particularly for relatively infrequent complications and implant survival.

Second, the follow-up period was limited to 6 months. This duration provides useful information regarding early implant positioning, peri-implant soft-tissue response, marginal bone changes, and initial prosthetic esthetics; however, it does not allow assessment of long-term implant stability, progressive marginal bone loss, peri-implant disease, prosthetic complications, or long-term esthetic maintenance.

Third, the study focused primarily on maxillary anterior implant sites, including central incisors, lateral incisors, and canine regions. Therefore, the findings may not be directly applicable to posterior implant sites or areas with substantially different anatomical and biomechanical conditions.

Fourth, assessment of esthetic outcomes using PES and WES involves a degree of clinical judgment, and observer-related variability cannot be completely excluded. Similarly, measurements of mucosal thickness, probing depth, and other peri-implant parameters may be influenced by measurement technique and examiner consistency.

Another limitation is that the study evaluated a relatively specific treatment protocol involving 3D orthodontic site optimization. Differences in orthodontic mechanics, implant planning methods, imaging protocols, operator experience, and

prosthetic procedures may influence the reproducibility of the findings in other clinical settings.

Finally, although multivariable regression was performed to identify factors associated with PES, the relatively small sample size limits the number of potential confounding variables that could be incorporated into the model. Consequently, residual confounding cannot be completely excluded. Larger studies with longer follow-up and standardized treatment protocols are required to confirm the observed relationships.

Conclusion

3D orthodontic optimization of implant sites was associated with greater accuracy of implant

placement and improved peri-implant and prosthetic esthetic outcomes compared with conventional implant planning. Optimized sites demonstrated reduced positional and angular deviations, more favorable peri-implant soft-tissue characteristics, lower marginal bone changes, and higher PES and WES values at 6 months. Greater implant-position deviations and probing depth were associated with poorer esthetic outcomes, whereas increased mucosal thickness was associated with higher PES. Overall, integrating orthodontic site optimization with 3D implant planning may improve the precision and predictability of anterior implant rehabilitation. Larger studies with longer follow-up are warranted to confirm these findings.

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