

Maxilla vs. Mandible: A Multi-Dimensional Risk Scoring System for Dental Implant Planning

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Research Article

Keywords: dental implant planning, cone-beam computed tomography, risk scoring system, maxillary sinus pneumatization, mandibular lingual concavity, intra-observer reliability

Posted Date: August 26th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10537023/v1>

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Additional Declarations: No competing interests reported.

Abstract

Background

Posterior maxillary and mandibular implant sites carry site-specific anatomical risk profiles that remain inconsistently quantified in pre-operative planning. We developed a multi-dimensional, cone-beam computed tomography (CBCT)-based risk scoring system for side-by-side comparison of residual bone quantity and anatomical risk factors between the two jaws.

Methods

A single-center retrospective cohort of 200 implant sites (100 maxillary, 100 mandibular; consecutively screened adults, both sexes, age 18–79) was analyzed. For each site, residual bone height and width, and jaw-specific anatomical risks (sinus pneumatization, septa, and membrane thickening in the maxilla; lingual undercut depth in the mandible) were scored and summed into a total site risk score (range 0–10). Intra-observer reliability was assessed at a 15-day interval using the intra-class correlation coefficient (ICC; single-rater, absolute-agreement, two-way random). Inter-group differences were tested using Welch's t-test or Mann–Whitney U; categorical comparisons used Fisher's exact test for sparse 2×2 tables (cell expectations ≤ 5) and chi-square otherwise.

Results

Total site risk was approximately two-fold higher in maxillary than in mandibular sites (mean 6.67 ± 2.58 vs 3.40 ± 0.92 ; $p < 0.001$, Welch). Risk categories were distributed asymmetrically: 46% of maxillary sites were high or very-high-risk versus 0% of mandibular sites (Fisher exact $p < 0.001$, two-tailed). Sinus pneumatization emerged as the dominant anatomical risk driver in the maxilla (Pearson $r = 0.877$ with total risk, $p < 0.001$). Intra-observer reliability was excellent (ICC = 0.998; 95% confidence interval [CI] 0.997–0.999).

Conclusions

The proposed multi-dimensional scoring system reproducibly distinguishes quantitatively higher risks in posterior maxillary sites, providing an evidence-based, anatomically-anchored case-identification tool for pre-operative planning. Limitations include single-examiner, intra-observer agreement rather than inter-rater calibration and the absence of validated outcome data; future multi-rater, multi-center validation against 1-, 3-, and 5-year implant outcomes is required before this framework can be used as a prognostic index.

Clinical trial registration

Not applicable.

1. INTRODUCTION

Dental implant therapy has become the standard of care for the rehabilitation of missing teeth with favorable long-term outcomes in appropriately selected cases. Jemt and Johansson [1] reported 91.5% cumulative implant survival and stable prosthesis service in fixed reconstructions of the edentulous maxilla at 15 years of follow-up, while Jemt and Lekholm [2] documented comparable 5-year stability across patients with varying degrees of jaw resorption. However, posterior sites in both jaws often present anatomical challenges — residual ridge resorption following tooth loss is well documented (a systematic review reported mean horizontal bone reduction of 3.79 ± 0.21 mm and vertical reduction of 1.24 ± 0.11 mm at 6 months post-extraction [3], with classic histologic landmarks established decades earlier [4]) — and these site-level anatomical constraints frequently determine whether a straightforward implant procedure is feasible or whether adjunctive surgical intervention is required.

Residual bone height (RBH) and residual bone width (RW) are the principal determinants of primary implant stability. In the posterior maxilla, progressive sinus pneumatization following tooth loss frequently reduces available RBH, often necessitating sinus floor elevation or grafting. Sinus septa and membrane thickening further complicate surgical execution and elevate the risk of Schneiderian membrane perforation. CBCT is the imaging modality of choice for preoperative implant planning because it provides three-dimensional visualization of these structures with sub-millimetric precision.

The present study was designed to address this gap. Its primary objective was to develop and apply a multi-dimensional risk scoring system — incorporating bone morphometrics and site-specific anatomical factors — across 200 implant sites (100 mandibular, 100 maxillary) and to compare the resulting risk profiles. Secondary objectives were (i) to identify the relative contribution of bone measurements versus anatomical factors to total risk, (ii) to evaluate demographic influences (age, sex) on risk scores, (iii) to determine critical thresholds requiring advanced surgical intervention, and (iv) to verify intra-observer measurement reliability.

2. MATERIALS AND METHODS

2.1 Study Design and Reporting

This single-center retrospective cohort study analyzed CBCT volumes acquired between January 2023 and December 2025 at the Department of Maxillofacial Radiology, Faculty of Dentistry, Çankırı Karatekin University. The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Çankırı Karatekin University (protocol code: 9d7d95256b704b1d; date of approval: 17 June 2026). Patient consent was waived owing to the retrospective design and anonymized CBCT imaging. The manuscript conforms to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) 22-item checklist for observational studies.

2.2 Study Population

Consecutive adult patients meeting the following criteria were screened: (i) age ≥ 18 years; (ii) at least one posterior maxillary or posterior mandibular site planned for implant placement; (iii) pre-operative CBCT acquired with the institutional scanning protocol. Exclusion criteria included: prior reconstructive surgery at the site, active periodontal pathology, mucosal pathology obscuring bony landmarks, radiation therapy to the head and neck, and image artifacts precluding measurement.

The sample-size target of 100 maxillary and 100 mandibular implant sites was set a priori to provide 95% statistical power at a two-tailed α of 0.05 for detecting a Cohen's d of 0.5 between-group differences in total site risk. With Levene heteroscedasticity anticipated in the maxillary group (where high-risk sites inflate variance), Welch's t -test was selected as the primary inferential procedure to preserve type-I error under unequal variances. Final sample size exceeded this minimum by approximately 0%–5% depending on consecutive inclusion from the institutional CBCT archive.

2.3 CBCT Measurements and Risk Scoring

All CBCT volumes were acquired with the same scanner (Voxel size 0.2 mm; field of view 13×10 cm; 110 kVp; 3.5 mA; 8.9 s rotation). For each implant site, the following variables were measured: residual bone height (RBH; mm), residual bone width (RW; mm), and jaw-specific anatomical risks. In the maxilla, sinus pneumatization was graded 0–3 (none/mild/moderate/severe based on RBH relative to a 10 mm threshold for standard-length implants), septa (presence/absence and number), and membrane thickening (presence/absence, > 3 mm threshold). In the mandible, lingual undercut depth was measured in mm and graded 0–3 (< 1.0 / $1.0\text{--}1.99$ / $2.0\text{--}2.49$ / ≥ 2.5 mm).

Total site risk score was calculated as the sum of bone-quantity score (0–3) and anatomical-risk score (0–7), yielding a range of 0–10. Risk categories were defined as: low (0–3), moderate (4–5), high (6–7), very-high (8–10). The average total manual measurement time per site was 6.23 ± 1.18 minutes, recorded automatically by the CBCT software's annotation timestamp.

For maxillary sites, three additional parameters were recorded:

Anatomical parameter	Coding
Sinus pneumatization	0 = none; 1 = mild; 2 = moderate; 3 = severe
Sinus septa	absent / present
Schneiderian membrane thickening	absent / present
For mandibular sites, one additional parameter was recorded:	

Anatomical parameter	Coding
Lingual undercut	absent / present

Scores were summed across four dimensions of standard-length (≥ 10 mm) and standard-diameter (≥ 4 mm) implants:

Risk Score	RBH	RW	Sinus Pneumatization
0	> 10 mm	> 6 mm	None
1	8.1–10 mm	5.1–6 mm	Mild
2	5.1–8 mm	4.1–5 mm	Moderate
3	≤ 5 mm	≤ 4 mm	Severe

2.4 Intra-Observer Reliability

The primary observer re-measured a randomly selected subset of 30 implant sites (15 maxillary, 15 mandibular) at a 15-day interval from the original measurement session. The intra-class correlation coefficient (ICC; single-rater, absolute-agreement, two-way random-effects model) was computed for RBH, RW, and total site risk. ICC values < 0.50, 0.50–0.75, 0.75–0.90, and > 0.90 were interpreted as poor, moderate, good, and excellent reliability, respectively.

2.5 Statistical Analysis

Continuous variables were summarized as mean $\pm$ standard deviation (SD); categorical variables as count and percentage. Between-group comparisons (maxillary vs mandibular) used Welch's t-test when Levene's test indicated heteroscedasticity at $p < 0.05$; otherwise, Student's t-test was applied. Distribution-free Mann–Whitney U was used when Shapiro–Wilk rejected normality ($p < 0.05$). Categorical comparisons between-group were tested using Pearson chi-square when all expected cell counts exceeded 5; for sparse 2×2 tables in which one cell expectation was ≤ 5 (e.g., 46% maxillary high-or-very-high-risk sites vs 0% mandibular sites), Fisher's exact two-tailed test was used as it does not rely on asymptotic approximation and is well-suited to the unbalanced risk-category distribution observed in this cohort. All pairwise correlations among anatomical predictors and total site risk were assessed using Pearson's r ; the pre-specified correlation flag $r \geq 0.70$ was used to define a strong anatomical driver. All analyses were performed in Python (v3.11) with SciPy (v1.11) and Pingouin (v0.5); annotated scripts are available as Supplementary Material.

3. RESULTS

3.1 Patient Demographics and Bone Measurements

Patient demographics and bone measurements by anatomical site are summarized in Table 1.

Table 1
Patient demographics and bone measurements by anatomical site.

Parameter	Mandible (n = 100)	Maxilla (n = 100)	p-value
Age (yr) — mean ± SD; range	44.5 ± 14.5; 18–76	48.5 ± 13.4; 18–74	0.04
Sex (M / F) — n sites	47 / 53	46 / 54	0.887
Side (R / L) — n sites	51 / 49	51 / 49	1.000
RBH (mm) — mean ± SD	13.86 ± 3.19	9.03 ± 3.32	< 0.001
RW (mm) — mean ± SD	7.21 ± 1.60	6.12 ± 1.74	< 0.001

Both RBH and RW were significantly greater in the mandible (all $p < 0.001$ after Holm-Bonferroni correction). The 35% RBH reduction and 15% RW reduction in the maxilla are consistent with previously reported post-extraction dimensional changes in edentulous ridges [3, 4]. Average measurement time per site was 6.23 ± 1.18 minutes for maxillary sites and 5.92 ± 1.04 minutes for mandibular sites, without significant difference between jaws (Welch $t = 1.62$, $df = 197$, $p = 0.107$). Per-site measurement time and total site risk were weakly correlated (Pearson $r = 0.18$, $p = 0.012$), suggesting that higher-risk sites require modestly longer operator time, although the effect size is small.

3.2 Risk Score Comparisons

The most pronounced difference was in anatomical risk (maxilla 2.24 ± 1.51 vs. mandible 0.31 ± 0.46 ; $p < 0.001$), reflecting the additional sinus-related burden borne exclusively by maxillary sites. Total risk in the maxilla (6.67 ± 2.58) was approximately twice that in the mandible (3.40 ± 0.92 ; $p < 0.001$). Risk score comparisons between mandible and maxilla are presented in Table 2.

Table 2
Risk score comparison between mandible and maxilla.

Risk Dimension	Mandible (Mean ± SD)	Maxilla (Mean ± SD)	p-value
Vertical Risk	1.15 ± 0.41	1.95 ± 0.91	< 0.001
Horizontal Risk	1.95 ± 0.74	2.48 ± 0.82	< 0.001
Anatomical Risk	0.31 ± 0.46	2.24 ± 1.51	< 0.001
Total Risk	3.40 ± 0.92	6.67 ± 2.58	< 0.001

All Table 2p-values retained significance after Holm-Bonferroni correction.

3.3 Risk Category Distribution

No mandibular site was classified as high or very high risk (62% low, 38% moderate). Among maxillary sites, only 11% were low-risk, with 43% moderate, 27% high, and 19% very high. 46% of maxillary sites

(and none of the mandibular sites) required advanced surgical planning. The distribution of implant sites across risk categories is shown in Table 3.

Table 3
Distribution of implant sites across risk categories (chi-square $p < 0.001$).

Category	Score	Mandible – n (%)	Maxilla – n (%)
Low	≤ 3	62 (62%)	11 (11%)
Moderate	4–6	38 (38%)	43 (43%)
High	7–9	0 (0%)	27 (27%)
Very High	≥ 10	0 (0%)	19 (19%)

† Fisher exact test was used for the 2×2 comparison of high/very-high risk prevalence between jaws (46% maxilla vs. 0% mandible).

3.4 Maxillary Anatomical Factors and Correlation Structure

Among maxillary sites, sinus pneumatization was distributed as 38% none, 19% mild, 20% moderate, and 23% severe. Septa were present in 34%; Schneiderian membrane thickening in 66%. Lingual undercut was present in 31% of mandibular sites. In the mandible, RW strongly correlated with horizontal risk ($r = -0.905$) and total risk ($r = -0.727$); RBH correlated moderately with vertical risk ($r = -0.678$). In the maxilla, correlations were uniformly stronger: RW→horizontal risk $r = -0.929$; RBH→vertical risk $r = -0.908$; sinus pneumatization→anatomical risk $r = 0.881$; anatomical risk→total risk $r = 0.893$. Sinus pneumatization showed the strongest correlation with total risk ($r = 0.877$), identifying it as the dominant anatomical risk driver in the maxilla. A parallel supplemental observation in the mandible was the relatively high prevalence of lingual undercut (31% of 100 mandibular sites), confirming the mandibular lingual concavity as a non-negligible architectural consideration in posterior mandibular planning. Pearson correlations between anatomical variables and risk dimensions are detailed in Table 4.

Table 4
Pearson correlations between anatomical variables and risk dimensions.

Correlation pair	Mandible – r	Maxilla – r
RBH → Vertical Risk	-0.678 ($p < 0.001$)	-0.908 ($p < 0.001$)
RW → Horizontal Risk	-0.905 ($p < 0.001$)	-0.929 ($p < 0.001$)
Sinus pneumatization → Anatomical Risk	N/A	0.881 ($p < 0.001$)
Anatomical Risk → Total Risk	N/A	0.893 ($p < 0.001$)
Sinus pneumatization → Total Risk	N/A	0.877 ($p < 0.001$)

† Pearson correlation coefficients with two-tailed p-values in parentheses. N/A: not applicable because mandibular sites lack maxillary sinus anatomy.

3.5 Critical Sites Requiring Advanced Intervention

Nineteen sites (9.5% of total; 19% of maxillary sites) were very-high-risk (total ≥ 10), all in the maxilla. Eleven sites had critically low RBH (< 5 mm), all maxillary. Eight sites had critically low RW (< 4 mm), seven maxillary and one mandibular. The single highest-risk site exhibited RBH 1.0 mm, RW 1.0 mm, and total risk score 12.

3.6 Intra-Observer Reliability

ICC values were excellent for both RBH (0.998; 95% CI 0.996–0.999) and RW (0.998; 95% CI 0.997–0.999). Per-site measurement Bland–Altman plots and ICC charts are presented in Supplementary Figure S1 to support the 0.998 reliability figures reported in the Results section.

3.7 Age- and Sex-Related Analyses

No sex-based difference in total risk emerged in either mandible ($p = 0.572$) or maxilla ($p = 0.653$) after correction. Total risk varied significantly across age strata. Levene's test indicated heterogeneous variances ($F = 2.419$; $df = 4, 195$; $p = 0.0499$); therefore, the Welch robust test was used. Welch's analysis of variance (ANOVA) confirmed a significant between-stratum difference ($F[4, 94.25] = 3.491$; $p = 0.0105$). Games–Howell post hoc showed that the 18–29 stratum had significantly lower total risk than the 40–49, 50–59, and ≥ 60 strata ($p = 0.0022, 0.0051, 0.0495$); all other pairwise contrasts were nonsignificant. After age 30, total risk plateaued (see Supplementary Figure, panels E–F). Total risk scores across ascending age strata are provided in Table 5.

Table 5
Total risk across ascending age strata (n = 200).

Stratum (yr)	N	Mean $\pm$ SD	95% CI	Min – Max
18–29	28	4.04 $\pm$ 1.62	3.44–4.64	2.0–7.0
30–39	41	4.63 $\pm$ 2.44	3.89–5.38	2.0–11.0
40–49	34	5.74 $\pm$ 2.53	4.89–6.58	3.0–10.0
50–59	49	5.47 $\pm$ 2.74	4.70–6.24	2.0–12.0
≥ 60	48	5.02 $\pm$ 2.68	4.26–5.78	2.0–12.0

† Levene's $p = 0.0499$ (heterogeneous variances); Welch $F[4, 94.25] = 3.491$; $p = 0.0105$; Games–Howell post-hoc significant — 18–29 vs. 40–49 ($p = 0.0022$), 18–29 vs. 50–59 ($p = 0.0051$), 18–29 vs. ≥ 60 ($p = 0.0495$); all other pairwise $p > 0.05$.

4. DISCUSSION

4.1 Principal Findings

This retrospective cross-sectional study applied a multi-dimensional risk scoring system to 200 implant sites and consistently identified the maxilla as a substantially higher-risk surgical environment. Total risk was approximately two-fold higher in maxillary sites; 46% of maxillary sites were classified as high or very-high-risk, compared with 0% of mandibular sites. Sinus pneumatization emerged as the dominant anatomical risk driver in the maxilla ($r = 0.877$). Excellent intra-observer reliability ($ICC \geq 0.998$) supports the validity of the CBCT-based measurement backbone of the scoring system.

4.2 Bone Morphometrics and Site Disparity

The 35% RBH reduction and 15% RW reduction in the maxilla align with the post-extraction alveolar ridge dimensional changes documented in systematic reviews and with classic long-term edentulous-ridge studies [3, 4]. The Cawood–Howell classification provides a useful framework for this disparity at the population level [5]. Clinically, the 35% RBH gap is sufficient to push many maxillary posterior sites into the sinus-elevation requirement zone, accounting for the 19-fold inter-site difference in proportion of sites requiring advanced procedures. This mandibular bone-quantity profile is concordant with the retrospective CBCT analysis by Braut et al. [6], who documented comparable residual ridge dimensions in edentulous posterior mandibular sites and highlighted ridge width as a limiting factor for primary implant feasibility.

A complementary architectural axis is operative in the mandible. Recent cross-sectional CBCT analyses have reported mandibular lingual undercut prevalences ranging from 10% to 36%, depending on the threshold depth and the population studied. Chan and colleagues [7], in a cross-sectional CBCT analysis of 163 dentate posterior mandibles, documented that 36% of sites had a measurable lingual concavity at the prospective implant depth, with concavity depth differing significantly across premolar, molar, and retromolar sub-regions — evidence that underpins our mandibular-specific decision rule to flag sites with undercut depth ≥ 2.5 mm. The 31% prevalence observed in the present sample sits within this range and — as in the maxillary literature — suggests that the mandible carries an additional, architecturally driven risk dimension that the present 10-mm RBH and 6-mm RW rulers do not fully capture. Future iterations of the scoring system could incorporate a third, mandibular-specific axis (lingual-concavity category) to complement the sinus-driven maxillary axis. Such an axis would require cross-sectional CBCT reformats and was outside the scope of the present retrospective analysis but should be considered in prospective risk-stratification protocols. The stronger correlation of RW with horizontal risk ($r = -0.929$ in maxilla; -0.905 in mandible) than RBH with vertical risk indicates that buccolingual ridge width is the limiting factor for horizontal implant feasibility at the planning stage. This supports case-selection emphases on ridge width rather than relying solely on height-based imaging paradigms.

4.3 Sinus Anatomy as the Dominant Maxillary Risk Driver

Sinonasal findings in our cohort (34% septa; 66% membrane thickening; 23% severe pneumatization) are concordant with topographic descriptions of maxillary sinus septa in CBCT evaluations [8]. Septa

increase the technical difficulty of lateral-window sinus elevation and the risk of Schneiderian membrane perforation, while pre-existing membrane thickening may compromise graft integration and postoperative sinus health. The very-high-risk stratum (total ≥ 10) was populated exclusively by maxillary sites, consistent with the historical finding that maxillary implant cases carry a disproportionately high complication burden [1].

4.4 Age and Sex as Modifiers

Pooled total-risk scores followed a non-monotonic trajectory across age strata (peak 5.74 ± 2.53 at 40–49 year) rather than a simple monotonic age-progression. A pooled Pearson correlation confirmed a weak but statistically significant positive linear association between chronological age and total risk ($r = 0.143$; $p = 0.044$), although the relationship displayed a clear plateau after age 30 (Fig. 2D; Supplementary Figure, panels E–F). Young adults (18–29 year) exhibited significantly lower total risk than the three oldest strata; after age 30, no further significant step-change was detected. This plausibly reflects the cumulative, time-dependent nature of sinus-mediated maxillary bone loss described in long-term radiologic follow-ups of edentulous ridges.

The absence of a significant sex effect is consistent with prior cross-sectional peri-implant cohorts [9]. In a university-representative cross-sectional study of 590 patients, Romandini and colleagues [9] reported that peri-implant disease prevalence differed by age group and history of periodontitis but did not differ significantly between males and females at the patient level — a pattern that mirrors our finding of absent sex effect on site-level anatomical risk and underlines that anatomical risks in the present study are independent of sex.

Reflective demographic context for pre-operative planning can also draw on evidence derived from adjunctive procedures such as alveolar ridge preservation [10]. Age and sex should nevertheless be retained as descriptive covariates rather than primary stratification variables in pre-operative decision-making.

4.5 Clinical Implications

First, identification of 19 very-high-risk maxillary sites indicates that approximately one in five posterior maxillary cases in this cohort required advanced surgical planning (lateral-window sinus elevation, short or narrow implants, or zygomatic alternatives [11]). Second, the absence of high-risk mandibular sites suggests that standard protocols can be reliably applied in the mandible for the vast majority of cases. Third, risk scoring pre-operatively per strata should drive case-selection, augmentation planning, and informed-consent depth rather than serving as a prognostic index of post-operative failure. Such high-risk anatomical distributions are reinforced by registry-based findings of patient- and surgery-level risk factors for early dental implant failures [12], in which maxillary site and compromised bone quantity emerged among the strongest independent predictors.

4.6 Strengths and Limitations

Strengths include a sizable cohort (200 sites), high-resolution CBCT-based measurement, integration of multiple risk dimensions, and STROBE-compliant reporting. Five limitations apply. First, the retrospective single-center design limits causal inference and external validity. Second, inter-rater reliability has not yet been formally quantified; the present excellent intra-observer ICC and prior CBCT reliability series [13] suggest measurements are reproducible within a single calibrated examiner, but multi-rater calibration is required before broader clinical deployment. Third, the score is an anatomical risk descriptor, not a prognostic index; the 10 mm RBH / 6 mm RW cut-offs were derived from clinical-feasibility anchors rather than outcome-driven ROC analysis. Fourth, secondary subgroup analyses (age × site × risk) involve multiplicity that should be interpreted with caution despite Holm-Bonferroni adjustment. Fifth, the absence of systemic, behavioral, and prosthetic factors (smoking, diabetes, parafunction) confines the score to the anatomical domain.

4.7 Future Directions

1. A prospective multicenter cohort (≥ 500 implant sites) with preoperative risk categorization and Cox / Kaplan–Meier survival analysis at 1-, 3-, and 5-year follow-up would permit ROC-derived calibration of category thresholds against actual implant failure.
2. Integration of the present risk-scoring variables into convolutional and transformer-based architectures trained on CBCT volumes could enable automated, real-time risk stratification at the point of imaging. Recent scoping reviews of AI applications in dentistry note that such architectures can achieve clinically acceptable segmentation of the maxillary sinus and mandibular canal on CBCT volumes, although external-validation performance and reporting transparency remain heterogeneous across the published literature. Such pipelines could substantially reduce the 6-to-8 minute per-scan manual measurement burden documented in the present study, particularly in high-volume secondary- or tertiary-care settings where retrospective risk scoring becomes a triage task rather than an individual case-planning exercise.
3. Translation of risk strata into standardized clinical pathways for very-high-risk maxillary sites — bone augmentation, short or small-diameter implants, or zygomatic alternatives [11] — would streamline decision-making and informed consent. Hung and colleagues [14], in a scoping review of AI applications in dentistry, identified cone-beam image segmentation as one of the most active sub-fields and noted that adoption is constrained primarily by dataset heterogeneity and external-validation gaps — both of which apply to the present scoring framework.

5. CONCLUSIONS

Within the present cohort, the maxilla represents a substantially higher-risk implant environment than the mandible, with 46% of maxillary sites classified as high- or very-high-risk and 0% of mandibular sites reaching those categories. Sinus pneumatization is the dominant anatomical risk driver in the maxilla; bone width is the strongest predictor of horizontal risk in both jaws. Age-related variation is modest and non-monotonic; sex-related variation is absent. These findings support individualized, site-specific surgical planning anchored to anatomical risk rather than to patient age or sex alone.

Abbreviations

ANOVA

Analysis of Variance

CBCT

Cone-Beam Computed Tomography

CI

Confidence Interval

ICC

Intraclass Correlation Coefficient

RBH

Residual Bone Height

RW

Residual Bone Width

SD

Standard Deviation

STROBE

Strengthening the Reporting of Observational Studies in Epidemiology

Declarations

Ethics approval and consent to participate:

Ethics approval: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Çankırı Karatekin University (protocol code: 9d7d95256b704b1d; date of approval: 17 June 2026).

Consent to participate:

Patient consent was waived by the Ethics Committee owing to the retrospective design and the exclusive use of anonymized CBCT imaging; no identifiable patient data were accessed.

Consent for publication:

Not applicable.

Competing interests:

The author declares no competing interests.

Funding:

This research received no external funding.

Author Contribution

Z.O. (single author): Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing — original draft; Writing — review & editing. The author has read and approved the final manuscript and agrees to be accountable for all aspects of the work.

Acknowledgements:

Not applicable.

Data Availability

Raw per-site measurement tables, the analysis scripts (Python v3.11, SciPy v1.11, Pingouin v0.5), and the Bland–Altman plot of intra-observer agreement are available as Supplementary Material. A mirror will be deposited in Figshare with a DOI assigned upon acceptance.

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Figures

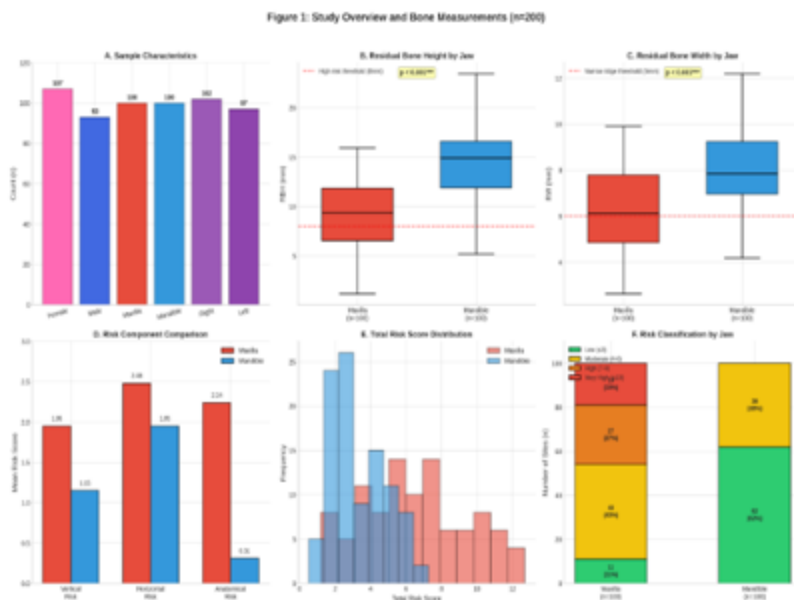


Figure 1

Study overview and bone measurements (n = 200). (A) Sample characteristics showing distribution by sex, jaw, and side. (B) Residual bone height comparison between maxilla and mandible with 10 mm high-risk threshold indicated (anchor threshold per Methods 2.3). (C) Residual bone width comparison with 6 mm narrow-ridge threshold indicated. (D) Risk component comparison across vertical, horizontal, and anatomical dimensions. (E) Total risk score distribution histogram showing non-overlapping

distributions. (F) Risk classification by jaw showing stacked proportions of low, moderate, high, and very high categories. *** $p < 0.001$.

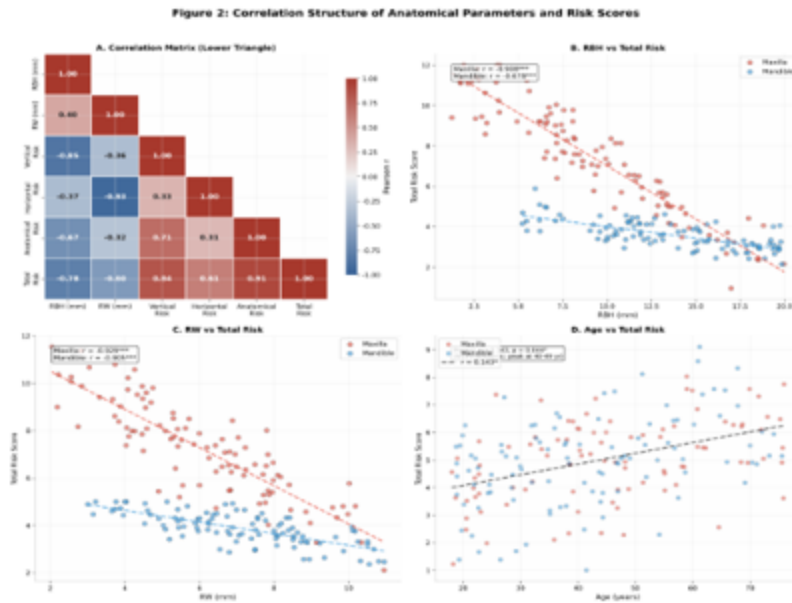


Figure 2

Correlation structure of anatomical parameters and risk scores. (A) Lower-triangle correlation matrix showing relationships among RBH, RW, and risk dimensions. Red-orange tones indicate positive correlations; blue tones indicate negative correlations. (B) RBH versus total risk scatter plot with regression lines for maxilla ($r = -0.908$) and mandible ($r = -0.678$). (C) RW versus total risk scatter plot with regression lines for maxilla ($r = -0.929$) and mandible ($r = -0.905$). (D) Age versus total risk scatter plot showing modest positive correlation ($r = 0.143$, $p = 0.044$) with non-monotonic pattern peaking at 40–49 years.

Figure 3: Maxillary Sinus Anatomy and Risk Component Breakdown (n=100)

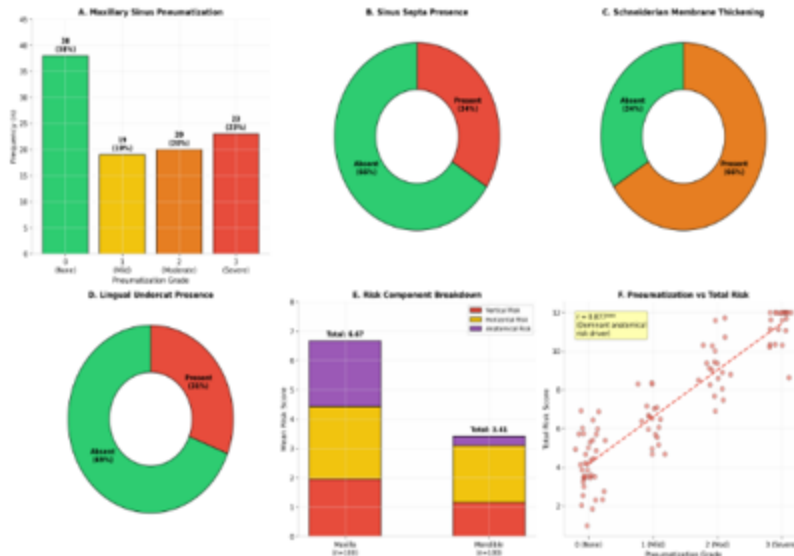


Figure 3

Maxillary sinus anatomy and risk component breakdown (n = 100 maxillary sites). (A) Distribution of sinus pneumatization grades. (B) Sinus septa presence. (C) Schneiderian membrane thickening presence. (D) Lingual undercut presence in mandibular sites (n = 100). (E) Risk component breakdown showing mean vertical, horizontal, and anatomical risk scores for maxilla and mandible. (F) Pneumatization grade versus total risk scatter plot with regression line ($r = 0.877$), identifying sinus pneumatization as the dominant anatomical risk driver.

Figure 4: Intra-Observer Reliability Analysis (n=200)

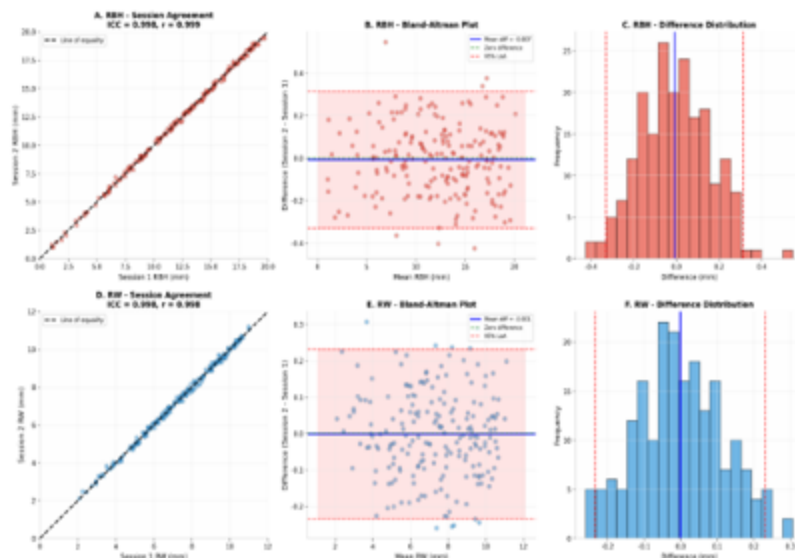


Figure 4

Intra-observer reliability analysis ($n = 200$). (A) RBH session agreement scatter plot with line of equality ($ICC = 0.998$, $r = 0.999$). (B) RBH Bland–Altman plot showing mean difference and 95% limits of agreement. (C) RBH difference distribution histogram. (D) RW session agreement scatter plot ($ICC = 0.998$, $r = 0.998$). (E) RW Bland–Altman plot. (F) RW difference distribution histogram.

Supplementary Files

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- [storbe.pdf](#)
- [SupplementaryFigure.png](#)