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Influence of torque-curve dynamics on initial bone remodeling around dental implants: a multicenter prospective study

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ABSTRACT

Purpose: This study investigated the relationship between implant insertion torque characteristics and initial bone remodeling (IBR) around the implant, moving beyond peak torque values to examine dynamic features of the torque–time curve. The primary research question was whether static, integral, and dynamic torque-derived parameters were associated with IBR under clinical conditions.

Methods: This study was conducted across 10 clinical centers and included 97 implants placed in healed ridges. Full torque-time curves were recorded during implant insertion using a surgical motor. Static torque metrics, torque-time and torque-depth integrals, regression-derived parameters, and indices of curve variability were extracted. Radiographic and clinical peri-implant bone levels were assessed at implant placement and after 3 months of submerged healing. Associations between torque-related variables and IBR were analyzed using mixed-effects linear regression models that accounted for patient-level clustering and potential confounders.

Results: Greater insertion torque magnitude, including mean, maximum, and final torque, was significantly associated with increased clinical IBR, particularly at the buccal aspect. Neither the torque-time integral nor the estimated torque-depth integral was associated with radiographic or clinical IBR. Dynamic descriptors of torque delivery, reflecting curve irregularity and nonlinear behavior, showed significant associations with buccal bone remodeling independent of torque magnitude. Lingual/palatal bone remodeling was less pronounced and was mainly related to torque magnitude.

Conclusions: Insertion torque was associated with initial peri-implant bone remodeling through both its magnitude and its dynamic delivery pattern. Global energy-based metrics appeared insufficient to describe marginal bone response under clinical conditions, whereas torque-curve characteristics provided additional information. These exploratory findings

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Trial Registration

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Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Author Contributions

Conceptualization: Claudio Stacchi, Giuseppe Troiano; Data curation: Claudio Stacchi, Teresa Lombardi, Graziano Montaruli, Marco Mozzati, Gianluca Gregorig, Marco Lollobrigida, Rosario Sentineri, Luca Lamazza, Gianmario Schierano, Giuseppe Troiano, Angela Tisci; Formal analysis: Giuseppe Troiano; Investigation: Claudio Stacchi, Teresa Lombardi, Graziano Montaruli, Marco Mozzati, Gianluca Gregorig, Marco Lollobrigida, Rosario Sentineri, Luca Lamazza, Gianmario Schierano, Giuseppe Troiano; Methodology: Claudio Stacchi, Giuseppe Troiano, Angela Tisci; Resources: Teresa Lombardi; Writing - original draft: Angela Tisci; Writing - review & editing: Claudio Stacchi, Teresa Lombardi, Graziano Montaruli, Marco Mozzati, Gianluca Gregorig, Marco Lollobrigida, Rosario Sentineri, Luca Lamazza, Gianmario Schierano, Giuseppe Troiano, Angela Tisci.

suggest that monitoring torque-curve dynamics may help identify implants at higher short-term risk of IBR and support timely preventive clinical measures.

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INTRODUCTION

Current evidence in implant dentistry indicates that insertion torque, long regarded as a purely mechanical parameter, has a complex biological role in early bone healing and, ultimately, long-term implant success [1,2]. Historically, high torque values were considered desirable because they correlated directly with primary stability [3,4], a prerequisite for osseointegration established in the foundational work of Brånemark and colleagues [5,6]. However, early implant stability depends not only on achieving high torque but also on the bone's tolerance of the mechanical compression generated during placement. Although excessive torque can provide excellent primary stability, overcompression may induce bone microdamage and ischemia, triggering a remodeling response that can substantially reduce mechanical anchorage during the transition from primary to secondary stability [7,8]. This effect is particularly important in cortical bone, whose high elastic modulus and limited deformation capacity reduce its tolerance to compressive overload. Exceeding these thresholds may amplify remodeling and increase the likelihood of peri-implant marginal bone resorption [8]. Initial bone remodeling (IBR), assessed both radiographically and clinically, is not merely a radiographic finding but may have important biological implications: recent evidence suggests that exposure of a micro-rough implant surface by ≥ 0.5 mm is significantly associated with progressive bone loss and long-term peri-implant disease [9-12].

Implant insertion also cannot be reduced to a single numerical parameter, such as final or peak torque, although this simplification has dominated much of the dental literature to date [13,14]. Final and peak insertion torque values capture only selected moments within a more complex mechanical pathway. Modern implant motors equipped with real-time torque-time monitoring make this limitation clear: rather than providing only an endpoint, they display the full torque profile, showing how resistance develops throughout insertion, how energy is delivered, and what pattern that delivery follows. From a biomechanical perspective, different torque curves likely impose distinct strain distributions within cortical and trabecular bone. Consequently, 2 implants that reach the same final torque may exert markedly different mechanical effects depending on whether that torque is reached gradually, abruptly, or through repeated peaks.

Recent investigations of parameters such as total insertion energy and torque-depth integrals have underscored this point [14-16]. These *in vitro* studies suggest that primary implant stability is influenced not only by peak insertion torque but also by how mechanical work accumulates during insertion. This represents an important shift away from the traditional reductionist view of torque as a single threshold for success. Nonetheless, these emerging metrics capture only part of the insertion process. A more complete assessment should also consider detailed torque-time curve characteristics, including initial resistance, the rate

of torque increase, nonlinear resistance patterns, and curve variability, together with the biological response of bone to the applied load [17]. These parameters may provide deeper insight into how mechanical work is delivered to bone and how tissue responds to different insertion patterns. A comprehensive evaluation of the relevant features of the insertion curve may therefore improve understanding of how to achieve primary stability while minimizing cortical overload and subsequent remodeling that could compromise marginal bone stability.

Therefore, the aim of this prospective multicenter study was to evaluate the association between different torque-related variables and peri-implant marginal bone stability from implant insertion to 3 months of submerged healing.

MATERIALS AND METHODS

Study design

This multicenter prospective observational study evaluated the association between torque-curve dynamics recorded during implant insertion and IBR. The study followed the Strengthening the Reporting of Observational Studies in Epidemiology guidelines and was conducted across 10 independent clinical centers in Italy. The protocol was reviewed and approved by the Ethics Committee of Regione Calabria, Sezione Area Nord (approval number: 73/2016). All procedures were performed in accordance with the Declaration of Helsinki (2024 revision) and Good Clinical Practice. The study was prospectively registered at ClinicalTrials.gov (identifier: NCT07019480). Written informed consent was obtained from all participating patients.

Eligibility criteria

Partially edentulous patients presenting for implant-supported prosthetic rehabilitation were considered eligible for inclusion if they met all of the following criteria: i) indication for implant-supported rehabilitation of single or multiple partial edentulism in the upper or lower jaw; ii) fully healed edentulous ridge, defined as ≥ 6 months after extraction; iii) residual crest width ≥ 6 mm; iv) residual crest height > 9 mm at the planned implant site; v) age ≥ 18 years; and vi) absence of removable prostheses at the planned implant site.

General exclusion criteria comprised the following: i) recent myocardial infarction (< 6 months); ii) uncontrolled coagulation disorders; iii) uncontrolled diabetes (glycated hemoglobin $> 7.5\%$); iv) head/neck radiotherapy within 24 months; v) immunocompromised status or recent chemotherapy; vi) past or current antiresorptive therapy; vii) severe psychiatric or cognitive conditions precluding the ability to understand the study procedures, provide informed consent, or reliably comply with the follow-up protocol; and viii) drug or alcohol abuse.

Sample size calculation

The sample size was determined *a priori* on the basis of the primary clinical analysis, which examined the association between continuous insertion-torque parameters and mean IBR at 3 months using mixed-effects linear regression. The minimum clinically relevant difference was set at 0.2 mm of mean IBR, in line with thresholds widely adopted in implant dentistry to distinguish physiological from pathological short-term peri-implant remodeling. Assuming an expected IBR variability of approximately 0.5 mm, a 2-sided α of 0.05, and a target statistical power of 0.80, at least 44 implants were required to detect the predefined clinically meaningful effect in a regression model adjusted for age, jaw, smoking status, supracrestal

tissue thickness, and primary stability. Because some patients contributed more than one implant, and to preserve valid inference under within-patient clustering, the minimum requirement was conservatively increased to 47 implants. Recruitment was then expanded to approximately 12 implants per center across 10 centers, for a total of 120 implants, to i) preserve adequate power across the multiple, mutually correlated torque-derived parameters extracted from each insertion curve and ii) account for a non-negligible proportion of post-enrollment exclusions due to intraoperative procedural deviations, such as noncontinuous rotational insertion (e.g., interrupted or intermittent movement, motor stalling, or manual completion), which compromise valid reconstruction of the torque-time curve even when the patient and implant site meet the *a priori* inclusion criteria.

Clinical procedures

All patients underwent cone-beam computed tomography (CBCT) for treatment planning, and a baseline periapical radiograph was obtained before surgery with standardized exposure settings (60 kV, 7 mA) using a customized Rinn-type holder and silicone positioning jig. Surgical procedures were standardized across participating centers according to an identical predefined protocol for the implant system, osteotomy preparation, and motor settings to ensure methodological consistency and minimize intercenter variability. After local anesthesia with 4% articaine and epinephrine 1:100,000, a minimally invasive full-thickness envelope flap was elevated. Supracrestal tissue height was measured at the implant site using a dedicated probe (SSL; Medesy srl, Maniago, Italy) and classified as thin (<2.5 mm), medium (2.5–3.5 mm), or thick (>3.5 mm) [18]. The implant bed was prepared according to the manufacturer's recommendations with a final osteotomy diameter of 3.6 mm, and a 4.0×8.5 mm tapered implant with an internal conical connection and moderately rough Ca²⁺-modified sandblasted and acid-etched surface was inserted at the crestal level (AnyOne; Megagen, Gyeongsan, Korea). Implant insertion was performed using a surgical motor (Implantmed SI-1023; W&H, Bürmoos, Austria) set at 30 rpm with rheostat modulation deactivated to ensure constant rotational speed. The torque limit was set at 80 Ncm. If full implant seating could not be achieved, the fixture was removed, and the osteotomy was enlarged with the next drill in the sequence (4.2-mm diameter) before reinsertion. Once the implant was seated in its final position, peri-implant bone levels were clinically assessed at the buccal and lingual/palatal midpoints using a UNC-15 periodontal probe, with measurements approximated to the nearest 0.5 mm. Immediately after implant placement, implant stability was assessed in four directions (mesiodistal, distomesial, buccolingual, and linguobuccal) using resonance frequency analysis (SmartPeg Type 07, Osstell Beacon; Osstell, Göteborg, Sweden); device calibration was verified before each surgery using a control implant embedded in resin.

Implants were then submerged by suturing the soft tissues with the Sentineri technique and single interrupted stitches using nonresorbable monofilament sutures [19]. Immediately after surgery, a periapical radiograph (T0) was obtained using the same customized holder and standardized acquisition procedures.

Postoperative medication included ibuprofen 600 mg as needed and 0.2% chlorhexidine rinses for 2 minutes three times daily, starting on postoperative day 2 [20]. Sutures were removed after 7–10 days.

Torque-curve data acquisition and processing

For each implant insertion attempt, the full torque-time curve was automatically recorded by the surgical motor and exported to a USB drive. To ensure accurate characterization of torque-time curves, implant insertion was performed with the aim of continuous advancement without intentional pauses or stop-and-go maneuvers. Cases involving interrupted or intermittent insertion were excluded from the analysis.

Torque-time data were initially extracted using WebPlotDigitizer (Automeris, Frisco, TX, USA) and then used for quantitative processing. Selected descriptive parameters were extracted directly from the torque-time curve, including maximum torque, final torque, and mean torque. Additional parameters were calculated through mathematical processing of the curve, specifically the torque-time integral and torque-depth integral.

Beyond descriptive and integral parameters, the torque-time curve was analyzed as a dynamic trajectory to characterize its overall behavior and potential irregularities in the insertion pattern. First, the data were modeled using least-squares linear regression, from which the intercept (β_0) and slope (β_1) were derived. In this framework, β_0 represents the theoretical torque value at the onset of insertion (**Figure 1**), whereas β_1 describes the average rate of torque increase over time (**Figure 2**), providing a synthetic measure of the progressive mechanical interaction between the implant and bone.

Because implant insertion is intrinsically nonlinear, the torque-time curve was further modeled using second-order polynomial regression. From this model, the quadratic coefficient (β_2) was extracted and used as a quantitative indicator of trajectory curvature, reflecting deviations from a linear increase in torque (**Figure 3**). This approach mirrors statistical strategies used to model longitudinal predictors through growth-curve parameterization, as described in previous methodological work on repeatedly measured predictors [21].

Finally, 2 distinct dispersion indices were calculated to quantify variability and irregularity in the torque-time curve: the residual standard deviation from the linear regression model ($r\sigma$) and the standard error of the quadratic model (σ_e) (**Figure 4**). Although both indices reflect irregularities in the insertion pattern, $r\sigma$ captures deviations from a purely

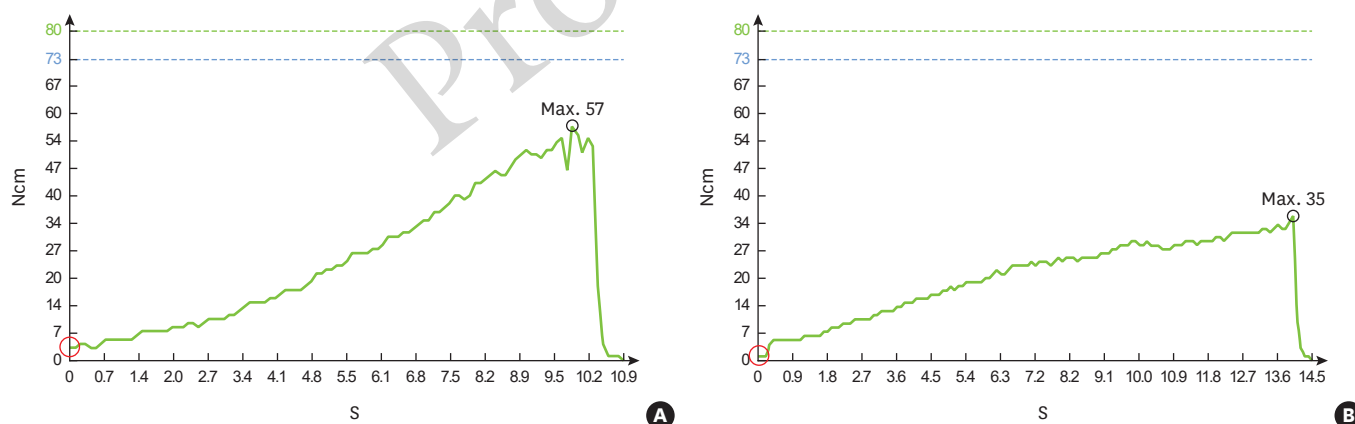


Figure 1. Torque-time curves showing different intercept (β_0) values.

The red circle marks the initial torque value at the beginning of insertion ($t=0$), corresponding to the intercept (β_0). (A) shows a higher β_0 value, indicating greater initial mechanical engagement, whereas (B) shows a lower β_0 value, indicating lower initial torque.

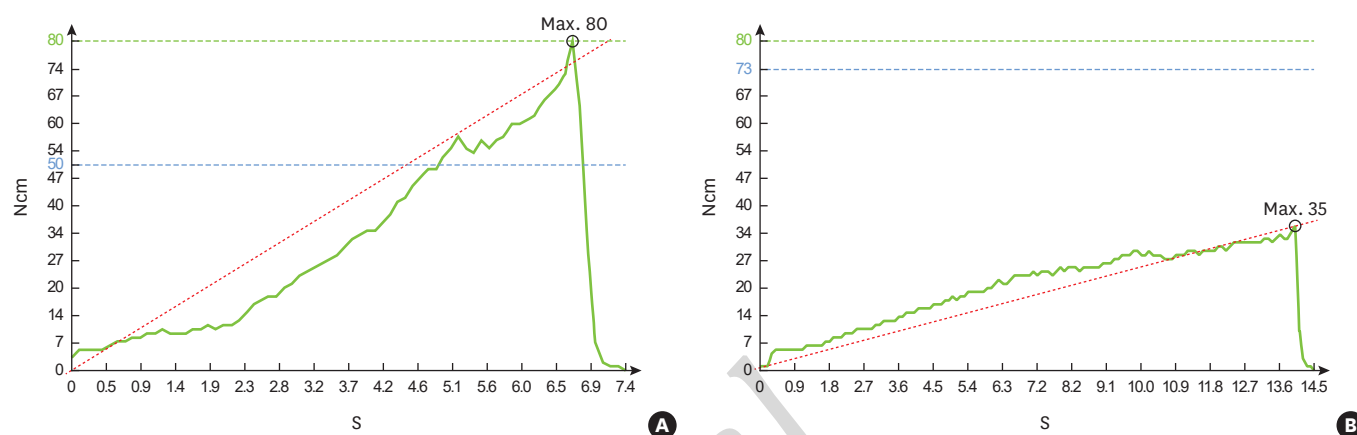


Figure 2. Torque-time curves showing different slope (β_1) values.

The red line represents the linear component of the torque-time regression model, corresponding to the slope (β_1). (A) shows a steeper slope, indicating a faster increase in torque over time, whereas (B) shows a flatter slope, indicating a slower torque increase.

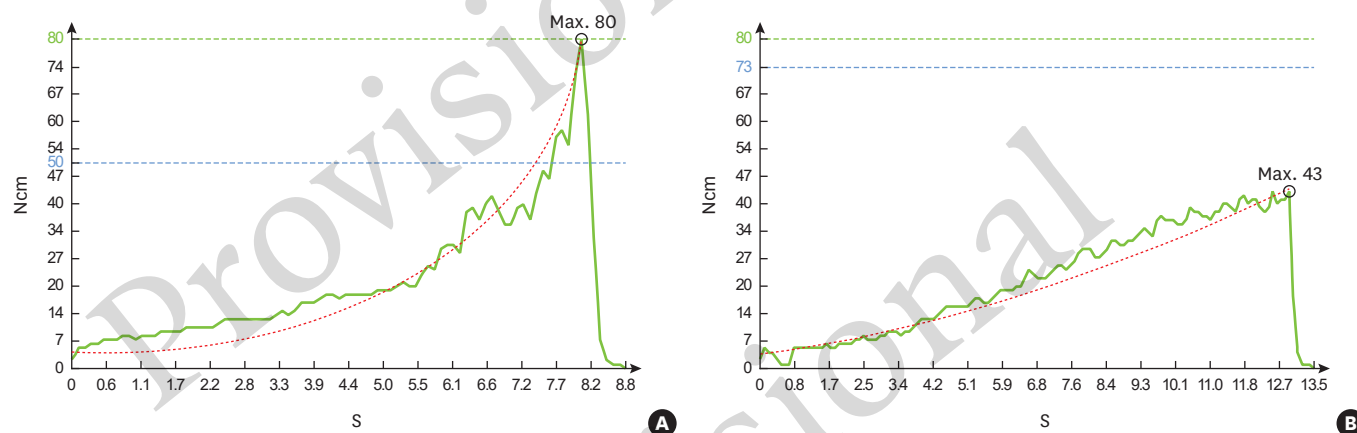


Figure 3. Torque-time curves showing different curvature (β_2) values.

The quadratic coefficient (β_2) describes the nonlinear component of torque increase over time. (A) shows a higher β_2 value, indicating a progressively changing rate of torque increase, whereas (B) shows a lower β_2 value, indicating a more uniform, near-linear torque increase.

linear trend, whereas σ_e measures unexplained variability after modeling the full quadratic structure of the torque-time profile (**Table 1**). None of these parameters is proposed as an independent biological entity; rather, each is a composite mechanical descriptor of the insertion event, influenced by implant macrodesign, osteotomy preparation, bone architecture, and operator technique.

All torque-time curve processing and modeling were performed in the R environment (version 4.5.1) using RStudio (Posit Software, Boston, MA, USA).

Follow-up procedures

After 3 months of submerged healing (T1), a periapical radiograph was obtained using the same individualized positioning device and standardized exposure settings across all centers. Implant uncovering was then performed to initiate prosthetic procedures, and implant stability quotient (ISQ) measurements were repeated according to the previously described protocol. During second-stage surgery, peri-implant bone levels were clinically assessed at the buccal and lingual/palatal midpoints of each implant after flap elevation using a UNC-

Table 1. Mechanical interpretation of torque-curve descriptors

Parameter	Mechanical meaning
β_0 (intercept)	Baseline insertion resistance at the start of implant placement, reflecting the initial mechanical engagement between the implant and the osteotomy.
β_1 (regression slope)	Average rate at which torque increases over time during insertion (how progressively or abruptly resistance builds up as the implant advances).
β_2 (quadratic coefficient)	Curvature of the torque-time profile (whether torque accumulates at a constant rate or accelerates/decelerates as insertion proceeds).
rSigma (residual SD, linear model)	Deviation of the actual curve from a purely linear trend (small-scale irregularity/oscillation around the overall slope).
σ_e (SE, quadratic model)	Fine-scale fluctuations of the torque signal remaining after accounting for the overall linear and quadratic shape of the torque-time curve, reflecting local irregularities during implant insertion.

SD: standard deviation, SE: standard error.

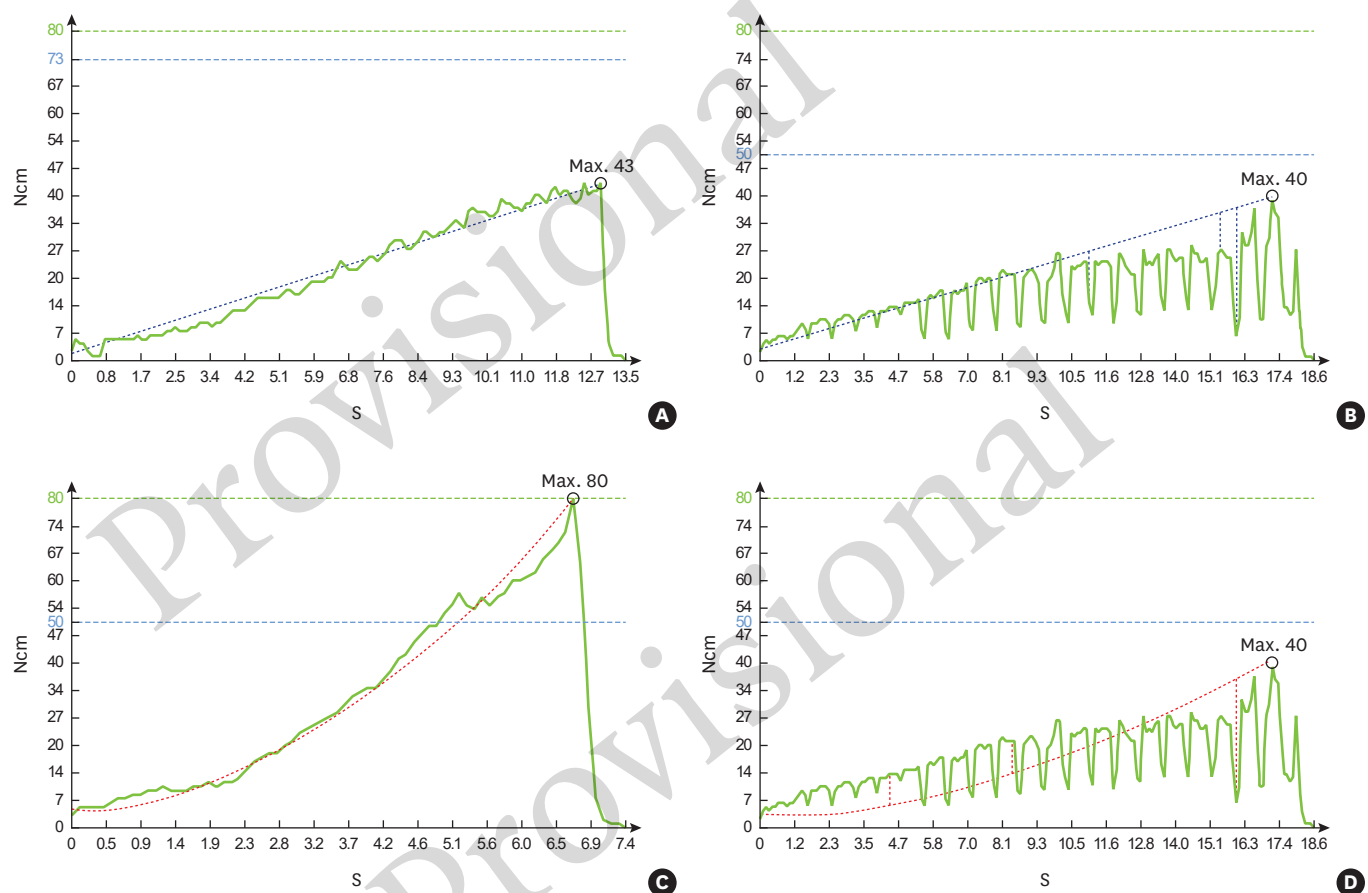


Figure 4. Illustration of rSigma and σ_e derived from linear and quadratic modeling of the torque-time curve.

Representative torque-time curves illustrating variability metrics derived from curve modeling. The purple line represents the linear regression model, and the red line represents the second-order polynomial regression model. Vertical dashed segments indicate residuals between the observed torque-time curve and the fitted models. (A, C) show insertion patterns characterized by low variability, corresponding to low rSigma and σ_e values. (B, D) show insertion patterns characterized by increased variability, corresponding to high rSigma and σ_e values.

15 periodontal probe, with measurements approximated to the nearest 0.5 mm. After an additional 4 weeks of healing, impressions were taken, and the definitive prosthesis, either a single screw-retained metal-ceramic crown or a multi-unit screw-retained metal-ceramic restoration, was fabricated.

Measurements

Radiographic peri-implant bone levels (PBLs) at T0 and T1 were measured on the mesial and distal aspects of each implant as the linear distance between the implant platform and

the most coronal bone-to-implant contact. Positive values indicated bone above the implant platform, whereas negative values indicated bone below the platform. Radiographic IBR was calculated as the difference in marginal bone level between T1 and T0. Measurements were performed by 2 examiners (A.T. and C.S.) using dedicated software (ImageJ; National Institutes of Health, Bethesda, MD, USA). Each measurement was repeated three times at separate time points. Before the study, the examiners were calibrated using 10 radiographs that were not included in the analysis. Intra- and interexaminer agreement were assessed using Cohen's κ coefficient, which was calculated by a third author (G.T.). The intra- and interexaminer agreement rates for linear measurements within ± 0.1 mm were 91.7% and 87.9%, respectively.

Statistical analysis

Descriptive statistics were used to summarize patient characteristics, implant sites, insertion torque metrics, regression-derived torque-curve parameters, implant stability measurements, and radiographic and intraoperative outcomes. Continuous variables were reported as means and standard deviations after assessment of distributional characteristics. Pairwise correlation analyses were performed to explore relationships between mechanical and clinical variables.

Spearman correlation analyses with Bonferroni correction were performed to assess the relationships between clinical buccal and lingual bone measurements and radiographic peri-implant bone loss at mesial and distal sites.

The torque-derived variables evaluated included maximum insertion torque, final insertion torque, mean insertion torque, torque-time integral, torque-depth integral, regression-derived intercept (β_0), regression-derived slope (β_1), quadratic coefficient (β_2), residual standard deviation from the linear regression model ($r\text{Sigma}$), and standard error of the quadratic model (σ_e). Implant stability was additionally assessed using ISQ values measured at T0 and T1 in the mesiodistal, distomesial, buccolingual, and linguobuccal directions, and subsequently averaged into a single mesiodistal and a single buccolingual value. The primary endpoint was the average radiographic IBR change at 3 months. For descriptive reporting, IBR was retained as a signed change, with negative values indicating bone loss. For regression analyses, IBR was analyzed as its absolute magnitude, such that higher values indicated a greater magnitude of bone remodeling. Because each patient could contribute up to three implants, multilevel mixed-effects linear regression models with random intercepts at the patient level were used to account for within-patient clustering. Center-level variability was preliminarily assessed by estimating the intraclass correlation coefficient (ICC) for the primary outcome, mean IBR, from a one-way random-effects null model with center as the grouping factor; the 95% confidence interval was obtained by cluster bootstrap resampling of centers with replacement ($B=2,000$). The estimated between-center variance converged to the boundary value of zero ($\text{ICC}=0.000$; $F[8,87]=0.56$, $P=0.811$), which was well below the 0.05 threshold below which Islam and Bangdiwala [22] showed by simulation that center can be safely ignored as either a fixed or random effect without biasing inference on the primary hypothesis. Given the negligible estimated center-level variance and the prespecified criterion, center was not included as a fixed or random effect in the primary models.

Separate univariable mixed-effects models were fitted for each torque-derived parameter to evaluate its association with radiographic IBR. The same modeling structure was also applied to vestibular and lingual bone resorption measured during second-stage surgery.

To adjust for potential confounding, multivariable mixed-effects linear regression models were then built by including the torque-related predictors of interest together with clinically relevant variables, such as age, jaw, and smoking status. Model performance and adequacy were assessed by selecting the specifications that minimized the Akaike information criterion and Bayesian information criterion. Additional diagnostic checks included likelihood-ratio tests, Wald statistics, and inspection of residual patterns to evaluate normality and homoscedasticity.

Exploratory stratified analyses were also performed separately for maxillary and mandibular implants to further assess the consistency of the associations between torque-derived parameters and peri-implant bone remodeling across jaw locations.

All analyses were performed using Stata version 16.1 (StataCorp, College Station, TX, USA). A two-sided *P* value <0.05 was considered statistically significant.

RESULTS

Participants and descriptive data

A total of 86 patients were enrolled across the 10 clinical centers, and 117 implants were placed between June and September 2025 (G.G.: 12; T.L.: 14; L.L.: 6; M.L.: 6; G.M.: 16; M.M.: 16; G.S.: 15; R.S.: 9; C.S.: 15; G.T.: 8). Twenty implants were excluded: 12 because subcrestal positioning prevented standardized radiographic measurements and 8 because intermittent or interrupted insertion resulted in invalid torque-curve acquisition. Thus, 97 implants with valid torque-curve recordings were included in the final analysis, providing adequate statistical power to detect the predefined clinically meaningful difference of 0.2 mm in mean IBR. The final cohort included 73 patients, comprising 39 male patients (53.4%) and 34 female patients (46.6%), with a mean age of 55.27±14.23 years. Among the 73 patients included in the analysis, 52 (71.2%) received one implant, 18 (24.7%) received two implants, and 3 (4.1%) received three implants. Most patients were nonsmokers (79.4%), and 12.3% reported a history of periodontitis. Soft-tissue phenotype at the crest was classified as thin in 36 implants (37.1%), medium in 44 implants (45.4%), and thick in 17 implants (17.5%) (**Table 2**).

Outcome data

Torque-curve metrics varied across inserted implants. The mean maximum insertion torque was 44.98±18.68 Ncm, final torque was 44.10±18.58 Ncm, and mean torque was 21.84±7.53 Ncm. The mean torque-time integral was 293.8±142.8 Ncm·s, and the mean torque-depth integral was 105.09±42.32 Ncm·mm. Extracted dynamic torque-curve variables had the following mean values: $\beta_0=0.48\pm5.19$, $\beta_1=3.33\pm2.64$, $\beta_2=0.15\pm0.48$, $\sigma_e=2.34\pm1.86$, and $r\text{Sigma}=3.38\pm2.68$. Mean baseline PBL was 0.097±0.79 mm at the mesial aspect and -0.035±0.54 mm at the distal aspect. After 3 months of submerged healing, PBL values were -0.231±0.90 mm at the mesial site and -0.386±0.87 mm at the distal site. Accordingly, radiographic IBR was -0.328±0.68 mm at the mesial aspect and -0.351±0.73 mm at the distal aspect, with an overall mean IBR of -0.343±0.62 mm when the two sites were averaged. At T1, clinically assessed IBR showed mean buccal bone resorption of -0.72±0.73 mm and mean lingual bone resorption of -0.29±0.49 mm. Regarding implant stability, mean baseline ISQ values were 74.19±12.48 in the mesiodistal direction and 73.60±11.72 in the buccolingual/palatal direction. After 3 months of submerged healing (T1), ISQ values increased to 79.09±9.44 in the mesiodistal direction and 77.61±12.49 in the buccolingual/palatal direction (**Table 3**). A strong positive correlation was observed between clinical marginal

Table 2. Demographic, clinical, and implant-related characteristics

Variable	Value
Patients	n=73
Age (yr)	55.27±14.23
Sex	
Male	39 (53.4%)
Female	34 (46.6%)
Smoking status	
Nonsmokers	58 (79.4%)
Smokers	15 (20.6%)
History of periodontitis	9 (12.3%)
Implants	n=97
Implants per patient	
1 implant	52 (71.2%)
2 implants	18 (24.7%)
3 implants	3 (4.1%)
Implant location	
Mandible	58 (59.8%)
Maxilla	39 (40.2%)
Soft-tissue thickness at crest	
Thin (<2.5 mm)	36 (37.1%)
Medium (2.5–3.5 mm)	44 (45.4%)
Thick (>3.5 mm)	17 (17.5%)

Values are presented as mean ± standard deviation or number (%).

Table 3. Descriptive statistics of torque-related variables, implant stability, and peri-implant bone levels

Variable	Value
Static torque parameters	
Maximum insertion torque (Ncm)	44.98±18.68
Final insertion torque (Ncm)	44.10±18.58
Mean insertion torque (Ncm)	21.84±7.53
Torque-time integral (Ncm·s)	293.8±142.8
Torque-depth integral (Ncm·mm)	105.09±42.32
Dynamic torque parameters	
β_0 (intercept)	0.48±5.19
β_1 (slope)	3.33±2.64
β_2 (quadratic coefficient)	0.15±0.48
σ_e (residual standard error)	2.34±1.86
rSigma (residual standard deviation)	3.38±2.68
Peri-implant bone levels (mm)	
Baseline PBL, mesial	0.097±0.79
Baseline PBL, distal	-0.035±0.54
3-month PBL, mesial	-0.231±0.90
3-month PBL, distal	-0.386±0.87
IBR mesial	-0.328±0.68
IBR distal	-0.351±0.73
Mean IBR (average of mesial and distal)	-0.343±0.62
IBR buccal	-0.72±0.73
IBR lingual	-0.29±0.49
ISQ	
ISQ mesiodistal (T0)	74.19±12.48
ISQ buccolingual (T0)	73.60±11.72
ISQ mesiodistal (T1)	79.09±9.44
ISQ buccolingual (T1)	77.61±12.49

Values are presented as mean ± standard deviation.

PBL: peri-implant bone level, IBR: initial bone remodeling, ISQ: implant stability quotient, T0: baseline, T1: 3-month follow-up.

bone loss measurements at the buccal and lingual aspects (Spearman's $\rho=0.69$, $P<0.001$). Clinical buccal and lingual measurements also showed moderate positive correlations with radiographic interproximal marginal bone loss (ρ range, 0.31–0.46; $P<0.01$).

Influences of torque variables on radiographic IBR

In univariable mixed-effects linear regression models with random intercepts at the patient level, patient- and site-related variables were analyzed to describe their potential associations with mean radiographic IBR at the mesial and distal implant aspects. Smoking status and maxillary implant location were significantly associated with mean radiographic IBR, whereas age, sex, history of periodontitis, and soft-tissue thickness were not significantly associated with this outcome.

Implant stability measures, including ISQ at T0 and T1 in both the mesiodistal and buccolingual directions, and the full set of torque-derived parameters are reported in **Table 4**. Overall, ISQ values were not significantly associated with mean radiographic IBR. Among the torque-related variables, parameters reflecting insertion torque magnitude were significantly associated with mean radiographic IBR. Mean insertion torque was significantly associated with mean radiographic IBR ($\beta=0.0163$ mm/Ncm; $P=0.034$), with similar effects observed for maximum insertion torque ($\beta=0.0091$ mm/Ncm; $P=0.003$) and final insertion torque ($\beta=0.0090$ mm/Ncm; $P=0.004$). In contrast, the torque-time integral, torque-depth integral, and coefficients derived from linear and quadratic regression models were not significantly associated with mean radiographic IBR. Among the remaining parameters, the residual standard deviation of the linear regression model (rSigma) was significantly associated with mean radiographic IBR ($\beta=0.049$ mm/Ncm; $P=0.019$), as was the standard error of the quadratic model (σ_e ; $\beta=0.073$ mm/Ncm; $P=0.014$).

In multivariable mixed-effects models adjusted for age, jaw location, and smoking status, maximum insertion torque ($\beta=0.0068$ mm/Ncm; $P=0.036$) and final insertion torque ($\beta=0.0067$ mm/Ncm; $P=0.040$) remained significantly associated with mean radiographic IBR. Among the dynamic torque-curve parameters, rSigma did not show statistical significance after adjustment ($\beta=0.037$ mm/Ncm; $P=0.090$), while retaining a consistent direction of effect. The σ_e parameter showed a borderline association with mean radiographic IBR ($\beta=0.054$ mm/Ncm; $P=0.077$).

Exploratory stratified analyses by jaw location showed a less homogeneous pattern for mean radiographic IBR than for clinical buccal bone remodeling. Most associations were not statistically significant in mandibular implants; however, several parameters were

Table 4. Mixed-effects analysis of torque-related parameters and mean IBR

Parameter	Univariable β	95% CI	P value	Adjusted β^*	95% CI*	P value*
ISQ T0 MD	-0.0014	-0.0111, 0.0083	0.776	-	-	-
ISQ T0 BL	-0.0036	-0.0138, 0.0065	0.482	-	-	-
ISQ T1 MD	-0.0087	-0.0215, 0.0042	0.186	-	-	-
ISQ T1 BL	0.0022	-0.0073, 0.0116	0.655	-	-	-
Maximum insertion torque	0.0091	0.0030, 0.0151	0.003	0.0068	0.0004, 0.0132	0.036
Final insertion torque	0.0090	0.0029, 0.0151	0.004	0.0067	0.0003, 0.0132	0.040
Mean insertion torque	0.0163	1.0012, 0.0325	0.034	0.0107	-0.0049, 0.0264	0.180
Torque-time integral	0.0001	-0.0007, 0.0009	0.794	-	-	-
Torque-depth integral	0.0013	-0.0014, 0.0041	0.341	-	-	-
β_0 (intercept)	-0.0136	-0.0352, 0.0080	0.217	-	-	-
β_1 (slope)	0.0286	-0.0141, 0.0713	0.189	-	-	-
β_2 (quadratic coefficient)	0.0038	-0.2327, 0.2404	0.975	-	-	-
σ_e (residual standard error)	0.0733	0.0147, 0.1319	0.014	0.0540	-0.0058, 0.1139	0.077
rSigma	0.0493	0.0079, 0.0906	0.019	0.0369	-0.0058, 0.0795	0.090

IBR: initial bone remodeling, CI: confidence interval, ISQ: implant stability quotient, T0: baseline, MD: mesiodistal, BL: buccolingual, T1: 3-month follow-up.

*Adjusted for age, jaw location, and smoking status.

significantly associated with mean radiographic IBR in maxillary implants, including rSigma ($\beta = -0.129$; $P = 0.003$), σ_e ($\beta = -0.186$; $P < 0.001$), and maximum insertion torque ($\beta = -0.010$; $P = 0.048$). Detailed results are reported in **Supplementary Table 1**.

Influence of torque variables on clinical IBR

In univariable mixed-effects analysis, maxillary implant location was significantly associated with buccal IBR ($\beta = 0.35$ mm; $P = 0.043$), whereas no significant associations were observed for the other patient-related variables or implant stability measures. For the lingual/palatal aspect, ISQ at T1 showed a significant or borderline association with IBR depending on the measurement direction (mesiodistal: $P = 0.055$; buccolingual: $P = 0.007$).

In univariable mixed-effects linear regression models with random intercepts at the patient level, insertion torque parameters were significantly associated with buccal IBR. Maximum insertion torque ($\beta = 0.024$ mm/Ncm; $P < 0.001$), final insertion torque ($\beta = 0.025$ mm/Ncm; $P < 0.001$), and mean insertion torque ($\beta = 0.053$ mm/Ncm; $P < 0.001$) were significantly associated with greater buccal bone resorption, indicating that higher insertion torque values were associated with increased marginal bone loss in this compartment. In contrast, integral parameters, represented by the torque-time integral and torque-depth integral, were not significantly associated with buccal IBR ($P = 0.383$ and $P = 0.100$, respectively). Among parameters derived from torque-time curve modeling, those obtained from linear and quadratic regression analyses were significantly associated with buccal marginal bone resorption. Both the intercept (β_0) and slope (β_1) of the linear regression were significantly associated with buccal IBR ($\beta_0: \beta = -0.056$ mm, $P < 0.001$; $\beta_1: \beta = 0.108$ mm/[Ncm/s], $P < 0.001$), suggesting that initial insertion conditions and the average rate of torque increase over time were related to the extent of marginal bone remodeling. Similarly, the quadratic coefficient (β_2) was significantly associated with buccal IBR ($\beta = 0.320$ mm/[Ncm/s²]; $P = 0.036$), indicating that greater curvature of the torque trajectory during insertion was associated with increased marginal bone loss. Finally, indices of variability and irregularity in the insertion pattern, represented by the residual standard deviation from the linear model (rSigma) and the standard error of the quadratic model (σ_e), were significantly associated with buccal IBR (rSigma: $\beta = 0.127$ mm/Ncm, $P < 0.001$; $\sigma_e: \beta = 0.143$ mm/Ncm, $P < 0.001$), indicating that insertion patterns characterized by greater torque irregularity were associated with increased bone loss.

In multivariable mixed-effects models adjusted for age, jaw location, and smoking status, associations for insertion torque magnitude parameters (maximum, final, and mean insertion torque) and for dynamic and irregularity-related parameters (β_0 , β_1 , β_2 , rSigma, and σ_e) remained statistically significant (all $P < 0.05$). These results support an independent association between both the magnitude and dynamic characteristics of implant insertion and buccal IBR. The full results of these mixed-effects regression analyses are presented in **Table 5**.

For the lingual/palatal compartment, the overall pattern was less pronounced than at the buccal aspect. With respect to insertion torque parameters, torque magnitude descriptors, including maximum, final, and mean insertion torque, were significantly associated with lingual/palatal marginal bone resorption (all $P < 0.05$), although effect sizes were smaller than those observed at the buccal aspect. In contrast, integral parameters, including torque-time and torque-depth integrals, and dynamic parameters derived from torque-time curve modeling, including β_0 , β_1 , β_2 , rSigma, and σ_e , were not significantly associated with lingual/palatal marginal bone resorption.

Table 5. Mixed-effects analysis of torque-related parameters and buccal IBR

Parameter	Univariable β	95% CI	P value	Adjusted β^*	95% CI*	P value*
ISQ T0 MD	-0.0003	-0.0129, 0.0122	0.952	-	-	-
ISQ T0 BL	-0.0037	-0.0171, 0.0097	0.589	-	-	-
ISQ T1 MD	-0.0067	-0.0235, 0.0100	0.428	-	-	-
ISQ T1 BL	-0.0088	-0.0213, 0.0038	0.172	-	-	-
Maximum insertion torque	0.0244	0.0180, 0.0308	0.000	0.0243	0.0173, 0.0313	0.000
Final insertion torque	0.0248	0.0185, 0.0311	0.000	0.0248	0.0179, 0.0317	0.000
Mean insertion torque	0.0530	0.0353, 0.0708	0.000	0.0501	0.0310, 0.0692	0.000
Torque-time integral	0.0005	-0.0006, 0.0016	0.383	-	-	-
Torque-depth integral	0.0031	-0.0006, 0.0068	0.100	-	-	-
β_0 (intercept)	-0.0560	-0.0822, -0.0298	0.000	-0.0528	-0.0786, -0.0270	0.000
β_1 (slope)	0.1084	0.0569, 0.1599	0.000	0.0972	0.0446, 0.1497	0.000
β_2 (quadratic coefficient)	0.3466	0.0458, 0.6473	0.024	0.3203	0.0217, 0.6189	0.036
σ_e (residual standard error)	0.1429	0.0670, 0.2187	0.000	0.1234	0.0444, 0.2224	0.002
rSigma	0.1271	0.0767, 0.1775	0.000	0.1168	0.0632, 0.1705	0.000

IBR: initial bone remodeling, CI: confidence interval, ISQ: implant stability quotient, T0: baseline, MD: mesiodistal, BL: buccolingual, T1: 3-month follow-up.

*Adjusted for age, jaw location, and smoking status.

Table 6. Mixed-effects analysis of torque-related parameters and lingual/palatal IBR

Parameter	Univariable β	95 % CI	P value	Adjusted β^*	95% CI*	P value*
ISQ T0 MD	-0.0010	-0.0094, 0.0075	0.820	-	-	-
ISQ T0 BL	-0.0053	-0.0138, 0.0065	0.253	-	-	-
ISQ T1 MD	-0.0108	-0.0219, 0.0003	0.055	-0.0114	-0.0228, -0.0000	0.050
ISQ T1 BL	-0.0113	-0.0195, -0.0030	0.007	-0.0127	-0.0212, -0.0041	0.004
Maximum insertion torque	0.0067	0.0011, 0.0123	0.020	0.0076	0.0015, 0.0136	0.014
Final insertion torque	0.0068	0.0012, 0.0125	0.018	0.0077	0.0016, 0.0138	0.013
Mean insertion torque	0.0167	0.0024, 0.0309	0.022	0.0184	0.0034, 0.0336	0.016
Torque-time integral	0.0003	-0.0004, 0.0011	0.365	-	-	-
Torque-depth integral	0.0012	-0.0014, 0.0037	0.363	-	-	-
β_0 (intercept)	-0.0182	-0.0374, 0.0010	0.063	-	-	-
β_1 (slope)	0.0268	-0.0141, 0.0713	0.170	-	-	-
β_2 (quadratic coefficient)	0.0333	-0.1769, 0.2434	0.756	-	-	-
σ_e (residual standard error)	0.0382	-0.0167, 0.0931	0.172	-	-	-
rSigma	0.0376	-0.0009, 0.0760	0.056	-	-	-

IBR: initial bone remodeling, CI: confidence interval, ISQ: implant stability quotient, T0: baseline, MD: mesiodistal, BL: buccolingual, T1: 3-month follow-up.

*Adjusted for age, jaw location, and smoking status.

In multivariable mixed-effects models adjusted for age, jaw location, and smoking status, the associations observed for torque magnitude parameters and ISQ values at T1 were generally confirmed. The full results of the mixed-effects regression analyses for lingual/palatal IBR are presented in **Table 6**.

Exploratory stratified analyses by jaw location showed that the association between higher insertion torque values and increased IBR remained generally consistent across maxillary and mandibular implants. Conventional insertion torque parameters, such as maximum insertion torque and final insertion torque, showed comparable directional associations in both anatomical regions. Conversely, some torque-curve-derived parameters varied in statistical significance and effect magnitude between jaws. Specifically, β_1 , rSigma, and σ_e remained significantly associated with buccal bone remodeling in both anatomical regions, whereas β_0 was significantly associated only in mandibular implants. For lingual/palatal remodeling, only rSigma and σ_e reached statistical significance, and only in maxillary implants. Detailed results are reported in **Supplementary Tables 2 and 3**.

DISCUSSION

This multicenter prospective study investigated the relationship between implant insertion mechanics and early peri-implant bone response, moving beyond the traditional use of peak or final insertion torque as the primary descriptor of the surgical procedure. The results confirm that insertion torque is not biologically neutral and suggest that both its magnitude and dynamic behavior during implant insertion may influence initial bone remodeling during early healing. Insertion torque is directly proportional to the compressive forces generated at the bone–implant interface during placement [23]. The magnitude and spatial distribution of these stresses are determined by osteotomy geometry and implant macrodesign. In most clinical situations, primary stability is achieved predominantly at the crestal cortical level, which is therefore the region where compressive loading is concentrated [24,25].

In this study, consistent with trends reported in recent reviews [1,26–28] and a Delphi consensus [29], higher insertion torque values were significantly associated with increased initial bone remodeling during the first 3 months of submerged healing. Mean, maximum, and final insertion torque all showed significant negative associations with marginal bone stability, with each 10-Ncm increase corresponding to approximately 0.09–0.17 mm of additional early bone loss. These findings support the concept that, although adequate torque is necessary for primary stability, excessive compression may create a biomechanical environment that exceeds the physiological tolerance of peri-implant bone, particularly at the crestal cortical level. Cortical bone has limited deformability and reduced capacity to dissipate compressive strains, making it especially vulnerable to compression-induced microdamage and ischemia, which may subsequently trigger an amplified remodeling response [8]. This mechanism provides a plausible biological explanation for the observed association between higher torque values and increased early bone loss. However, this interpretation should be regarded as a hypothesis explaining the observed statistical association rather than as a demonstrated biological mechanism, because bone quality, cortical thickness, and trabecular architecture were not independently quantified in this cohort.

From a clinical perspective, these findings suggest that insertion torque should be managed as a balance between achieving adequate primary stability and avoiding excessive mechanical compression of peri-implant bone. Although higher insertion torque values were associated with increased early remodeling, primary stability remains a fundamental requirement for predictable osseointegration. Accordingly, the relationship between insertion torque and IBR should not be interpreted in isolation but within the broader biological and mechanical context of implant healing. In this regard, Norton's concept of "viable constraint" highlights the importance of achieving sufficient mechanical stability while respecting the physiological tolerance of peri-implant bone [23]. Consistent with this concept, clinical evidence has shown that successful osseointegration and stable peri-implant conditions may also be achieved at relatively low insertion torque values when adequate primary stability is present [30]. This interpretation is further supported by recent evidence suggesting that excessively high insertion torque values may increase compressive strain and peri-implant bone remodeling, particularly when values exceed 50 Ncm [1], whereas very high torque values (>100 Ncm) have also been associated with increased postoperative discomfort and less favorable biological responses [31].

The magnitude of radiographic IBR observed in this study remained within ranges generally considered clinically acceptable. Nevertheless, accumulating evidence suggests that even limited early bone loss may have relevant biological implications [9,11]. Cortical compression

generated during implant insertion should be regarded as only one of multiple determinants of IBR, whose overall expression likely results from the interaction of surgical and prosthetic factors. Surgical variables such as crestal bone thickness, local crest morphology, and surgical trauma may modulate the bone response to insertion-related stresses. Prosthetic factors, including supracrestal tissue attachment, implant–abutment connection, abutment height, and the emergence profile of the definitive restoration, also play a critical role in crestal bone stability [2]. Within this multifactorial context, longitudinal studies have shown that early remodeling exceeding 0.5 mm results in exposure of the treated implant surface to the oral environment, thereby facilitating bacterial colonization and predisposing patients to progressive peri-implant bone loss over time [9-12,32]. Accordingly, the modest yet consistent differences in early remodeling associated with insertion torque may represent a biological signal that interacts with other determinants of long-term peri-implant tissue stability.

A key strength and novel aspect of this study is the comprehensive analysis of the insertion torque curve; to the authors' knowledge, the simultaneous evaluation of multiple torque-related variables has not previously been reported in clinical implant research. Although static torque parameters remained important predictors [1,23,28-31], additional descriptors of curve irregularity, specifically residual variability metrics derived from linear and quadratic modeling, were significantly associated with increased bone remodeling. Implants inserted with more heterogeneous and irregular torque profiles experienced greater early bone loss, even after adjustment for patient-related confounders. These findings suggest that not only the amount of torque applied but also its delivery over time may influence the peri-implant tissue response. Biomechanically, irregular torque-time patterns likely reflect fluctuating resistance during insertion, resulting in repeated localized stress concentrations within bone. Such intermittent compression may elicit microfracture formation and compromise microvascular perfusion, particularly at the crestal bone level. In this context, two implants that achieve identical final torque values may subject bone to substantially different mechanical damage depending on whether torque accumulation occurs gradually or through abrupt peaks and oscillations. However, torque-curve irregularity and the other derived parameters should not be interpreted as independent or directly controllable biological predictors. Rather, they reflect the combined influence of implant design, surgical technique, local bone characteristics, and operator-related factors and are better considered composite descriptors of the implant–bone interaction during insertion. From a clinical perspective, torque-curve analysis may provide real-time feedback on the biomechanical environment encountered during implant insertion, offering a “snapshot” of the interaction between implant and bone. In this context, unfavorable torque curve profiles, particularly when associated with high insertion torque, may help clinicians identify situations at higher risk of excessive bone remodeling and support immediate corrective decisions, such as minor simultaneous horizontal bone augmentation procedures. At this stage, this clinical utility should be regarded as an early chairside risk-flagging tool for the initial healing phase rather than as a validated long-term prognostic instrument; its value in predicting implant survival or long-term marginal bone stability remains to be established.

The analysis of buccal and lingual/palatal bone remodeling further supports this interpretation. At the buccal aspect, which is typically characterized by thinner cortical bone and reduced biological reserve, both static torque magnitude and dynamic curve descriptors showed strong and consistent associations with bone loss. Exploratory stratified analyses by jaw location further indicated that these associations remained generally consistent across maxillary and mandibular implants, particularly for conventional insertion torque

parameters and dynamic descriptors such as β_1 , $rSigma$, and σ_e . In contrast, lingual or palatal remodeling appeared less sensitive to curve variability and more modestly influenced by torque magnitude alone, with some dynamic parameters reaching statistical significance only in maxillary implants. Similarly, stratified analyses of radiographic mean IBR showed a less homogeneous pattern between jaws, with several associations observed predominantly in maxillary sites. This asymmetry likely reflects anatomical and biomechanical differences in cortical thickness and vascularization [33,34], emphasizing that insertion mechanics may interact with local bone morphology to determine remodeling outcomes.

In this study, neither the torque-time integral nor the estimated torque-depth integral was associated with radiographic or clinical IBR. Although these measures quantify the cumulative mechanical work applied during implant insertion, evidence supporting their relevance largely derives from *in vitro* investigations focused on primary mechanical stability [15,17,35-39]. Those studies address mechanical outcomes and do not assess the biological response of peri-implant bone under clinical conditions. When biological outcomes are considered, global energy-based metrics may therefore be insufficient to capture the localized mechanical conditions that influence initial peri-implant bone remodeling.

Several limitations of this study should be acknowledged. One relevant methodological aspect concerns the different nature of the radiographic and clinical outcomes. Periapical radiographs allowed standardized assessment of mesial and distal interproximal bone changes but could not depict buccal or lingual/palatal cortical remodeling. For this reason, direct clinical measurements were included to capture the site-specific component of IBR. The convergence between radiographic and clinical findings supports the overall interpretation, although the buccal and lingual/palatal data should be considered the most anatomically informative outcomes for evaluating cortical remodeling. In addition, the observational design precludes causal inference, and the follow-up period was limited to the early healing phase. The torque-depth integral was also estimated under the assumption of constant rotational speed and uniform thread advancement, because real-time angular displacement could not be directly recorded with the surgical motor used in this study. Consequently, this parameter should be interpreted as an approximation rather than a true measure of mechanical work. Nevertheless, under the controlled insertion conditions used here, expected variability in rotational speed and thread advancement was limited, supporting the robustness and practical reliability of this approximation for comparative analyses. Moreover, although several surgical and anatomical variables were prospectively standardized through strict eligibility criteria and protocol calibration across centers, important site-specific biological determinants were not quantitatively controlled. In particular, bone quality, cortical thickness, buccal bone dimensions, tooth position, implant adjacency, and implant site location may substantially influence both torque-curve behavior and initial peri-implant bone remodeling. Although all patients underwent CBCT-based treatment planning, site-specific anatomical variables, such as buccal and lingual/palatal cortical thickness and local bone density, were not quantitatively measured or entered into the multivariable models. This limitation was partly mitigated by the inclusion of healed ridges with adequate horizontal bone dimensions and by the use of a standardized surgical protocol. Nevertheless, residual differences in local bone anatomy may still have influenced the observed associations.

Center/operator effects represent a separate potential source of variability. In this study, intercenter variability was specifically assessed for the primary outcome and was found to be negligible; therefore, center was not retained in the final models.

Finally, the generalizability of these findings may be limited by the use of a single implant system and the inclusion of sites with favorable bone conditions, defined as crestal bone thickness ≥ 6 mm. In narrower crests, initial bone remodeling in response to high insertion torque could plausibly be more pronounced.

In summary, this study moves beyond the traditional view of insertion torque as a single numerical target and shows that both torque magnitude and dynamic behavior are associated with initial peri-implant bone remodeling. These findings support a more comprehensive biomechanical interpretation of implant insertion, in which controlled and homogeneous torque delivery may be as important as achieving adequate primary stability. The results should be regarded as hypothesis-generating rather than confirmatory, given the observational design, absence of independent bone-quality assessment, and limited follow-up period. Future studies should validate these observations in larger and more heterogeneous cohorts that include different implant systems and should incorporate quantitative CBCT-derived measurements of site-specific anatomical variables, such as cortical thickness, buccal bone dimensions, and local bone density, to better isolate the independent contribution of torque-curve dynamics. Further research should also explore the development of surgical devices capable of providing real-time feedback on insertion torque dynamics. Immediate access to such information could allow clinicians to identify unfavorable insertion patterns intraoperatively and promptly implement corrective measures, such as minor horizontal bone augmentation, aimed at compensating for possible initial bone remodeling and improving long-term peri-implant tissue stability.

SUPPLEMENTARY MATERIALS

Supplementary Table 1

Exploratory stratified mixed-effects analyses of torque-derived parameters associated with radiographic mean IBR according to jaw location

Supplementary Table 2

Exploratory stratified mixed-effects analyses of torque-derived parameters associated with vestibular IBR according to jaw location.

Supplementary Table 3

Exploratory stratified mixed-effects analyses of torque-derived parameters associated with lingual/palatal peri-implant bone remodelling according to jaw location

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