

e-ISSN: 2345-0592 <b>Online issue</b> Indexed in <i>Index Copernicus</i>	<b>Medical Sciences</b>  Official website: <a href="http://www.medicosciences.com">www.medicosciences.com</a>	
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## **Mechanical stability thresholds and their influence on osseointegration in posterior maxillary implants: a systematic review**

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### **Abstract**

**Background.** Successful implant therapy depends on osseointegration, which is strongly influenced by primary implant stability. Stability is commonly assessed using insertion torque and resonance frequency analysis. However, implant placement in the posterior maxilla remains challenging due to low bone density and anatomical limitations, and no clear consensus exists regarding optimal mechanical stability thresholds in this region.

**Aim.** To evaluate the relationship between primary implant stability measured by insertion torque and implant stability quotient and osseointegration outcomes in implants placed in the posterior maxilla.

**Methods.** Searches were conducted in PubMed/MEDLINE, ScienceDirect, and Springer Nature Link for studies published between 2016 and 2026. Eligible studies included randomized controlled trials and cohort studies reporting quantitative stability measures and osseointegration-related outcomes. Study selection, data extraction, and risk-of-bias assessment were performed independently by two reviewers using RoB 2 and ROBINS-I.

**Results.** Of 782 identified records, five studies met the inclusion criteria. These included two randomized controlled trials, two prospective clinical studies, and one retrospective cohort study with sample sizes ranging from 46 to 122 implants and follow-up periods from 5 months to 10 years. Moderate stability levels, typically insertion torque values of 20-35 N·cm and ISQ values of 55–65, were consistently associated with favorable outcomes, including high implant survival and minimal marginal bone loss. Surgical technique influenced primary stability but differences diminished during healing.

**Conclusions.** Moderate primary mechanical stability appears sufficient for predictable osseointegration in posterior maxillary implants, while long-term outcomes are also influenced by biological and anatomical factors.

**Keywords:** dental implants, posterior maxilla, primary implant stability, osseointegration, insertion torque.

## 1. Introduction

Dental implants represent a predictable treatment modality for the rehabilitation of partially and completely edentulous patients, with long-term survival rates frequently exceeding 90% in clinical studies [1]. The success of implant therapy relies on osseointegration, defined as a direct structural and functional connection between living bone and the implant surface. This process depends on both mechanical and biological factors during early healing, particularly the achievement of sufficient primary implant stability at the time of placement [1,2].

Primary stability reflects the mechanical engagement between the implant and surrounding bone immediately after placement and is influenced by bone density, implant macrodesign, surgical technique, and osteotomy preparation [1]. Insufficient stability may allow excessive micromotion at the bone-implant interface, which can disrupt the formation of new bone and lead to fibrous encapsulation rather than osseointegration. Experimental and clinical evidence suggests that micromotion exceeding approximately 50–150  $\mu\text{m}$  may compromise implant integration [3].

Clinically, primary implant stability is most commonly assessed using insertion torque (IT) and resonance frequency analysis (RFA), expressed as the implant stability quotient (ISQ). Insertion torque reflects rotational resistance encountered during implant placement, whereas RFA evaluates the stiffness of the implant-bone interface and allows longitudinal monitoring of stability changes over time [4]. Several studies report that torque values around 30–45  $\text{N}\cdot\text{cm}$  are frequently used as thresholds for immediate or early loading, while ISQ values above

approximately 60–65 are often considered indicative of adequate stability [4,5].

The posterior maxilla presents particular challenges for implant therapy due to lower bone density, reduced cortical thickness, and frequent sinus pneumatization. These anatomical characteristics may compromise primary stability and increase the risk of early implant failure. Although quantitative measures such as insertion torque and ISQ are widely used to guide clinical decision-making, there is no universal consensus on the stability thresholds required to ensure predictable osseointegration, especially in low-density maxillary bone [6].

Variability in surgical protocols, implant designs, stability measurement techniques, and outcome reporting has limited the ability to derive consistent clinical recommendations. Consequently, a focused synthesis of available clinical evidence is needed to clarify the relationship between mechanical stability thresholds and osseointegration outcomes in this anatomically challenging region.

Therefore, the aim of this systematic review was to evaluate the current evidence regarding mechanical stability thresholds and their influence on osseointegration outcomes in posterior maxillary implants, with particular emphasis on quantitative stability measures and their association with implant survival, marginal bone changes, and stability progression during healing.

## 2. Methods

### 2.1 Protocol and Registration

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [7]. The protocol was prospectively registered with the

International Prospective Register of Systematic Reviews (PROSPERO; registration ID: CRD420261333955). The research question was

formulated using the PICO framework presented in Table 1.

**Table 1.** PICO Framework

Component	Description
<b>P (population)</b>	Adult patients receiving dental implants in the posterior maxilla (native bone or grafted bone).
<b>I (intervention)</b>	Implants placed under defined mechanical stability thresholds (e.g., insertion torque, RFA/ISQ, micromotion limits).
<b>C (comparison)</b>	Implants placed with lower or higher stability values, or without reported quantitative thresholds.
<b>O (outcome)</b>	Primary: Osseointegration success (clinical/radiographic stability, survival). Secondary: MBL, implant survival/failure, ISQ progression, peri-implant complications.

*RFA – Marginal bone loss; ISQ – Implant Stability Quotient; MBL – Marginal bone loss*

## 2.2 Eligibility Criteria

### 2.2.1 Inclusion Criteria

- Human studies evaluating implants placed in the posterior maxilla
- Randomized controlled trials, controlled clinical trials, and prospective or retrospective cohort studies
- Quantitative mechanical stability measurement (insertion torque [N·cm], ISQ values, or micromotion thresholds)
- Reporting at least one osseointegration-related outcome
- Minimum follow-up of 3 months
- Articles published in English

### 2.2.2 Exclusion Criteria

- Case reports or case series (<10 implants)
- In vitro or animal studies
- Studies lacking quantitative stability measurements
- Studies evaluating implants exclusively in the anterior maxilla or mandible
- Reviews, editorials, or letters

## 2.3 Information Sources and Search Strategy

A comprehensive electronic search was conducted from January 1, 2025 to February 1, 2026. The following databases were searched: PubMed/MEDLINE, ScienceDirect and Springer Nature Link. The search was limited to human studies published in English between January 2016 and January 2026. The Boolean search strategy combined the following key terms: (Posterior maxilla) AND (dental implant) AND (osseointegration OR implant survival) AND (primary stability OR mechanical stability). All records were imported into EndNote reference management software, and duplicates were removed prior to screening. Reference lists of included studies were manually screened for additional eligible articles. Grey literature and trial registries were not systematically searched.

## 2.4 Study Selection

The study selection process was conducted independently by two reviewers (R.S. and I.S.) under the supervision of a senior investigator (Ž.P.). The selection proceeded in three phases: initial title screening to assess topic relevance,

abstract screening to evaluate compliance with the predefined eligibility criteria, and full-text review to determine final inclusion. Any disagreements between reviewers were resolved through discussion and consensus, with a third reviewer consulted when necessary. The entire selection process will be summarized and illustrated using a PRISMA flow diagram, detailing the number of records identified, screened, excluded, and included in the final analysis.

### 2.5 Data Extraction

Two reviewers (R.S. and I.S.) independently extracted data using a standardized data extraction form developed specifically for this review. The form was piloted on three eligible studies to ensure clarity, consistency, and completeness prior to full data extraction.

Extracted variables included study design and characteristics, patient demographics, implant-related parameters, quantitative mechanical stability measures, osseointegration-related outcomes, follow-up duration, and reported study limitations.

Discrepancies between reviewers were resolved through discussion and consensus. If agreement could not be reached, a senior reviewer (Ž.P.) was consulted to adjudicate the final decision.

### 2.6 Data Items

Data extracted from the included studies were organized into predefined categories as follows:

- Study identification: Author and year of publication
- Study design: Randomized controlled trial, controlled clinical trial, prospective or retrospective cohort study
- Sample size: Number of patients and/or implants evaluated

- Patient characteristics: Age, sex distribution, bone quality (if reported), and sinus augmentation status (native or grafted posterior maxilla)
- Implant characteristics: Implant system, surface characteristics, macrodesign, diameter, length, and loading protocol (immediate, early, or delayed)
- Mechanical stability parameters: Insertion torque (N·cm), resonance frequency analysis (RFA), implant stability quotient (ISQ) at placement and follow-up, and reported micromotion thresholds ( $\mu\text{m}$ )
- Comparator or threshold definition: Predefined stability cut-offs or comparison groups (e.g., high vs. low torque,  $\text{ISQ} \geq 70$  vs.  $< 70$ )
- Osseointegration-related outcomes: Implant survival/failure rate, marginal bone level changes (mm), secondary stability progression (ISQ evolution), and biological or mechanical complications
- Key findings: Principal results concerning the association between mechanical stability thresholds and osseointegration outcomes

### 2.7 Risk of Bias Assessment

The methodological quality of included studies was assessed using design-specific validated instruments. Randomized controlled trials were evaluated using the Revised Cochrane Risk of Bias tool (RoB 2) [8], which assesses internal validity across five domains:

- (1) bias arising from the randomization process;
- (2) bias due to deviations from intended interventions;
- (3) bias due to missing outcome data;
- (4) bias in measurement of the outcome; and
- (5) bias in selection of the reported result.

Each domain was evaluated using the signaling questions and decision algorithms provided in the RoB 2 framework and rated as “low risk of bias,” “some concerns,” or “high risk of bias.” An overall judgment was assigned according to Cochrane guidance, based on the highest level of risk identified across domains.

Non-randomized studies were assessed using the Risk Of Bias In Non-randomized Studies – of Interventions (ROBINS-I) tool [9], which evaluates seven domains: confounding; selection of participants; classification of interventions; deviations from intended interventions; missing data; measurement of outcomes; and selection of the reported result.

Each domain was rated as “low,” “moderate,” “serious,” or “critical” risk of bias, and an overall study-level judgment was derived according to ROBINS-I guidance.

Risk-of-bias assessments were conducted independently by two reviewers (R.S. and I.S.). Disagreements were resolved through discussion and consensus, with arbitration by a third reviewer (Ž.P.) when necessary.

## 2.8 Synthesis Methods

Due to substantial clinical, methodological, and outcome heterogeneity among the included studies, a quantitative meta-analysis was not performed. Heterogeneity was observed in study design (randomized controlled trials, prospective clinical studies, retrospective cohorts), surgical protocols (immediate placement, lateral sinus floor elevation, short implants), implant macrodesign, bone quality, and loading strategies.

Mechanical stability was assessed using heterogeneous metrics, including insertion torque (reported as means  $\pm$  standard deviations, ranges, or minimum threshold criteria) and

resonance frequency analysis (ISQ values reported as means or medians with interquartile ranges). Follow-up duration varied widely (5 months to 10 years), and osseointegration-related outcomes were inconsistently defined and reported (implant survival, marginal bone level changes, secondary stability progression, late implant failure).

Because comparable effect estimates with associated measures of variance at standardized time points were not consistently available, statistical pooling and formal heterogeneity assessment (e.g., Q statistic, I<sup>2</sup>) were not considered methodologically appropriate.

Accordingly, a structured narrative synthesis was conducted. Studies were organized into thematic categories based on stability-related variables:

- Surgical technique and primary stability
- Implant macrodesign and stability–bone relationships
- Low mechanical stability thresholds in atrophic posterior maxilla
- Stability progression during healing

The synthesis summarizes study characteristics, quantitative stability measures (torque and ISQ ranges), osseointegration outcomes, statistical associations, and sources of variability. Numerical findings are presented descriptively in structured summary tables to facilitate transparent comparison while avoiding inappropriate quantitative aggregation.

## 2.9 Reporting Bias Assessment

Because no meta-analysis was conducted and the number of included studies was limited, formal statistical assessment of publication bias (e.g., funnel plot asymmetry or Egger’s regression test) was not considered appropriate.

Potential reporting bias was therefore evaluated qualitatively. This involved:

- Comparing outcomes specified in the methods sections with those reported in the results
- Assessing completeness of reporting of mechanical stability parameters (insertion torque and ISQ values)
- Evaluating whether predefined osseointegration outcomes were selectively omitted
- Reviewing transparency in reporting follow-up duration and attrition

Selective outcome reporting was additionally assessed within the “selection of the reported result” domain of the RoB 2 tool for randomized studies and the corresponding domain of the ROBINS-I framework for non-randomized studies.

Any suspected reporting bias was documented narratively in the Results section.

### 3. Results

#### 3.1 Study Selection

The electronic search identified 782 records. After removal of 98 duplicate citations, 684 studies underwent title and abstract screening. Following this process, 43 full-text articles were assessed for eligibility. Based on the predefined inclusion and exclusion criteria, five studies fulfilled all eligibility requirements and were included in the qualitative synthesis [10–14].

These studies investigated quantitative mechanical stability parameters – specifically insertion torque and/or ISQ – in implants placed in the posterior maxilla, and reported at least one osseointegration-related outcome, including marginal bone loss, implant survival, late implant failure, or secondary stability progression.

The included studies comprised randomized controlled trials, prospective case–control studies, and retrospective cohort analyses evaluating the influence of mechanical stability on osseointegration outcomes in posterior maxillary implants.

The PRISMA flow diagram illustrating the study selection process is presented in Figure 1.

#### 3.2 Study Characteristics

Key characteristics of the included studies are summarised in Table 2. The five included investigations were published between 2021 and 2025 and consisted of two randomized controlled trials, two prospective clinical studies, and one retrospective cohort study. All studies evaluated implants placed in the posterior maxilla and reported quantitative primary mechanical stability measures in relation to osseointegration-related outcomes.

Sample sizes ranged from 46 implants [10] to 122 implants [12]. Follow-up duration varied considerably, from 5 months [13] to a mean of 10 years [12].

Clinical targets across studies included:

- Primary and secondary implant stability assessed by ISQ [10,13];
- Peri-implant marginal bone remodeling (PBR/MBL) [11,12,14];
- Implant survival and late implant failure (LIF) [12,14];
- Influence of surgical technique on mechanical stability [13];
- Immediate implant placement accuracy and its clinical impact [14].

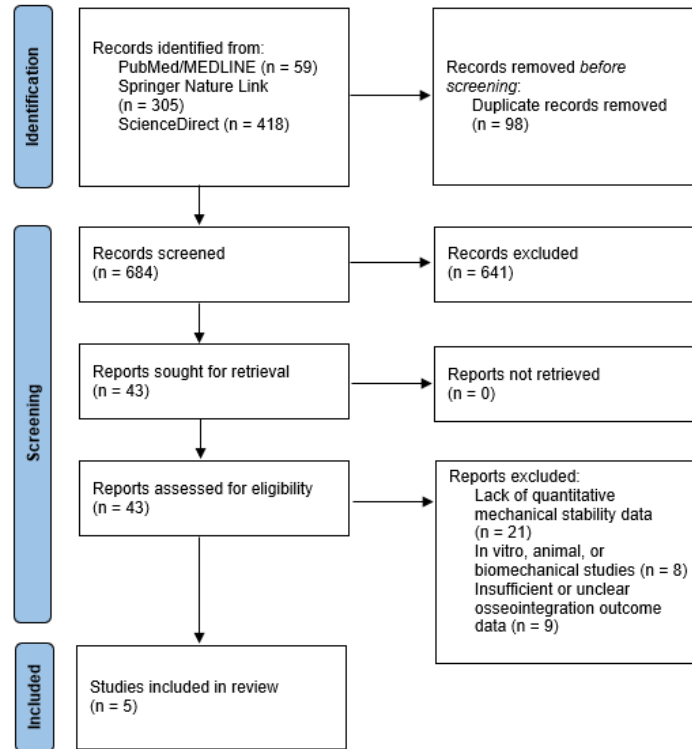
Primary mechanical stability was assessed using:

- Insertion torque (N·cm) [12,14];
- Resonance frequency analysis (ISQ) [10,11,13];
- Or a combination of both [11].

Comparators included different surgical techniques (osteotome vs conventional vs guided) [13], implant macrodesigns (tissue-level vs bone-level) [11], navigation-assisted vs

freehand placement [14], and evaluation of long-term risk factors affecting marginal bone loss and implant failure [12].

**Figure 1.** PRISMA flow diagram



**Table 2.** Key Characteristics of Included Studies

Author (Year)	Study Design	Number of Patients / Implants	Surgical Procedure	Intervention	Comparator	Mechanical Stability Measure(s)	Osseointegration Outcome(s)	Timing of Assessment
Al-Hity et al., 2025 [10]	Prospective clinical study	14 / 46	Posterior maxillary implant placement	Standard implant placement protocol	Maxilla vs mandible subgroup comparison	ISQ (AnyCheck RFA)	Secondary stability progression	Baseline; 3 months; 6 months
Lombardi et al., 2025 [11]	Controlled clinical study	58 / 71	Short implants in posterior maxilla	Tissue-level implants	Bone-level implants	Insertion torque; ISQ	Marginal bone remodeling; survival	Implant placement; 12 months
Dung et al., 2025 [12]	Retrospective cohort study	60 / 122	One-step lateral sinus floor elevation (LSFESI)	Implants placed with torque >15 N·cm	No direct comparator (risk-factor analysis)	Insertion torque (minimum threshold)	Marginal bone loss; late implant failure; survival	Placement; long-term follow-up (mean 10 years)
Planinić et al., 2021 [13]	Randomized clinical trial	150 / 150 (posterior maxilla subgroup)	Posterior maxillary implant placement	Osteotome technique	Conventional drilling; flapless guided placement	ISQ (Ostell)	Secondary stability	Baseline; 5 months
Yang & Geng, 2024 [14]	Randomized controlled trial	60 / 96	Immediate implant placement in posterior maxilla	Dynamic navigation-assisted placement	Freehand placement	Insertion torque	Marginal bone resorption; implant survival	Placement; mean 27.8 months

### 3.3 Risk of Bias in Included Studies

The risk of bias of the included studies was assessed using the Revised Cochrane Risk of Bias tool for randomized trials (RoB 2) [8] and the Risk Of Bias In Non-randomized Studies – of Interventions (ROBINS-I) tool [9], according to study design. The results are summarized in Tables 3 and 4 and visually presented in Figures 2 and 3.

Overall, the two randomized controlled trials were judged to have low to some concerns of risk of bias across assessed domains. One trial was rated as low risk of bias, while the second was assessed as having some concerns, primarily related to outcome measurement procedures and limited reporting of blinding. No substantial issues were identified regarding randomization, missing outcome data, or selective reporting.

Among the three non-randomized studies, overall risk of bias ranged from moderate to

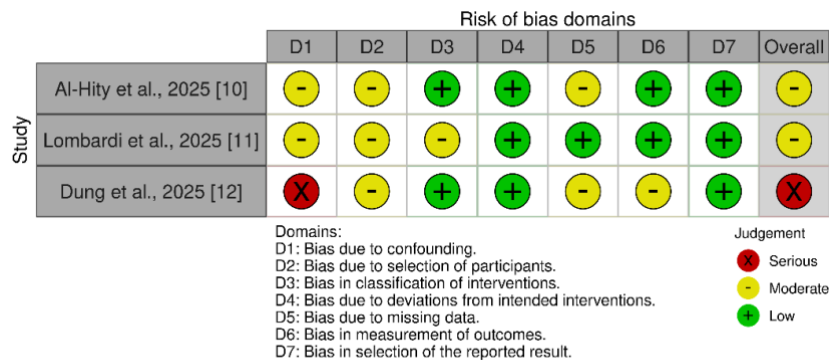
serious. Two studies were judged to have moderate risk of bias, mainly due to potential confounding factors such as bone quality, implant design, and surgical technique, as well as participant selection in single-centre settings. One long-term retrospective cohort study was assessed as having serious risk of bias due to unadjusted confounding and variability in baseline clinical characteristics that may have influenced both mechanical stability and osseointegration outcomes.

Across all studies, selective reporting bias was considered low. However, methodological limitations inherent to observational designs should be considered when interpreting the reported associations between mechanical stability measures and osseointegration in posterior maxillary implants.

**Table 3.** Risk of Bias Assessment of Non-Randomized Studies (ROBINS-I)

Study	Confounding	Selection of Participants	Classification of Interventions	Deviations from Intended Interventions	Missing Data	Measurement of Outcomes	Selection of Reported Results	Overall Risk
Al-Hity et al., 2025 [10]	Moderate	Moderate	Low	Low	Moderate	Low	Low	Moderate
Lombardi et al., 2025 [11]	Moderate	Moderate	Moderate	Low	Low	Low	Low	Moderate
Dung et al., 2025 [12]	Serious	Moderate	Low	Low	Moderate	Moderate	Low	Serious

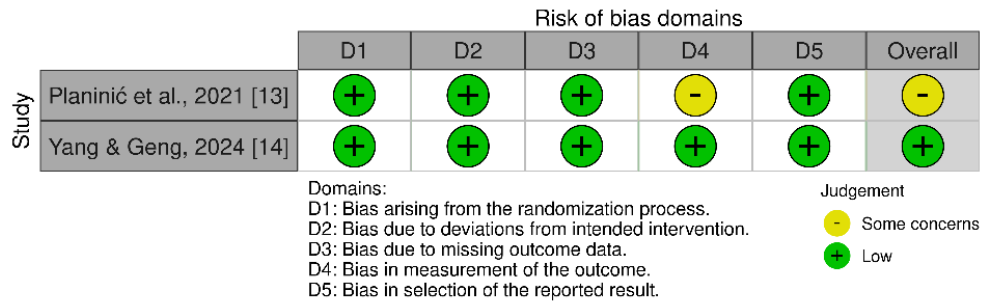
**Figure 2.** ROBINS-I risk-of-bias traffic-light plot



**Table 4.** Risk of Bias Assessment of Randomized Controlled Trials (RoB 2)

Study	Randomization Process	Deviations from Intended Interventions	Missing Outcome Data	Measurement of Outcome	Selection of Reported Result	Overall Risk
Planinić et al., 2021 [13]	Low	Low	Low	Some concerns	Low	Some concerns
Yang & Geng, 2024 [14]	Low	Low	Low	Low	Low	Low

**Figure 3.** ROB-2 risk-of-bias traffic-light plot



### 3.4 Results of Individual Studies

#### 3.4.1 Surgical Technique and Primary Stability

Two randomized clinical trials [13,14] evaluated the influence of surgical technique on primary mechanical stability in posterior maxillary implants.

In the randomized study by Planinic et al. [13], three preparation techniques (osteotome, conventional drilling, and flapless guided placement) were compared. The osteotome technique demonstrated significantly higher primary ISQ values compared with the other techniques ( $p < 0.01$ ). However, at 5 months, secondary ISQ values converged across groups, and no statistically significant intergroup differences were observed ( $p = 0.660$ ). These findings suggest that although surgical under-preparation may enhance early mechanical engagement, biological osseointegration reduces these differences during healing.

Similarly, Yang and Geng [14] compared navigation-assisted and freehand immediate

implant placement in the posterior maxilla. The mean insertion torque was  $24.38 \pm 1.84$  N·cm, with no statistically significant difference between groups. At a mean follow-up of  $27.8 \pm 8.4$  months, implant survival was 100% in both groups. However, marginal bone resorption was significantly lower in the navigation group. Mesial bone loss was  $0.19 \pm 0.88$  mm (navigation) versus  $0.25 \pm 1.46$  mm (freehand), and distal bone loss was  $0.31 \pm 0.66$  mm versus  $0.54 \pm 1.08$  mm, respectively ( $p < 0.05$ ). These findings indicate that moderate torque values around 24 N·cm were sufficient for predictable osseointegration, while surgical accuracy influenced crestal bone preservation.

#### 3.4.2 Implant Macrodesign and Stability–Bone Relationship

One controlled clinical study [11] evaluated the interaction between implant macrodesign, insertion torque, ISQ, and marginal bone remodeling in posterior maxillary implants.

In Lombardi et al. [11], insertion torque values ranged between approximately 25 and 40 N·cm, and a statistically significant positive correlation was identified between insertion torque and ISQ ( $p < 0.05$ ). At 12 months, implant survival was 100%.

Radiographic marginal bone level changes, reflecting peri-implant bone remodeling, differed significantly between implant designs. Tissue-level implants demonstrated mean bone remodeling of  $0.11 \pm 0.27$  mm at T1 and  $0.30 \pm 0.23$  mm at T2, whereas bone-level implants showed  $0.34 \pm 0.35$  mm at T1 and  $0.55 \pm 0.42$  mm at T2. The difference between designs was statistically significant ( $p = 0.003$ ).

These findings suggest that primary stability within a moderate torque range (25–40 N·cm) was compatible with successful osseointegration, but implant macrodesign influenced peri-implant crestal bone remodeling.

### 3.4.3 Stability in Severely Atrophic Posterior Maxilla

The long-term retrospective cohort study by Dung et al. [12] evaluated implants placed in severely atrophic posterior maxillae using a one-step lateral sinus floor elevation technique.

Implant placement required a minimum insertion torque threshold of  $>15$  N·cm. Over a mean follow-up period of approximately 10 years, overall implant survival was 87.7%, with a late implant failure rate of 12.3%. Marginal bone loss greater than 1 mm was observed in 16.8% of implants.

Importantly, multivariate analysis identified reduced keratinized tissue width ( $<2$  mm), sinus membrane perforation, and poor oral hygiene as

significant predictors of late implant failure, whereas the initial mechanical stability threshold itself was not independently associated with failure.

These findings suggest that even relatively low torque thresholds ( $>15$  N·cm) may be sufficient to achieve osseointegration in augmented posterior maxilla, although long-term success depends on peri-implant biological and anatomical factors.

### 3.4.4 Stability Progression During Healing

Two studies [10,13] specifically evaluated stability progression over time using resonance frequency analysis.

In Al-Hity et al. [10], posterior maxillary implants demonstrated a baseline ISQ median of 55 (IQR 51–61). ISQ values increased significantly at 3 and 6 months, with a statistically significant improvement at 6 months ( $p = 0.0006$ ), indicating progressive biological stabilization.

Similarly, Planinić et al. [13] demonstrated that although primary ISQ differed significantly between surgical techniques ( $p < 0.01$ ), secondary stability values at 5 months were not significantly different ( $p = 0.660$ ), reflecting convergence of mechanical stability during osseointegration.

Across studies, primary ISQ values in posterior maxilla typically ranged between 55 and 65, and torque values ranged from  $>15$  N·cm to approximately 40 N·cm, suggesting that moderate mechanical stability levels were generally sufficient for predictable osseointegration.

**Table 5.** Summary of Mechanical Stability Thresholds and Osseointegration Outcomes

Stability Category	Included Studies (n)	Stability Range Reported	Osseointegration Outcome	Overall Interpretation
Surgical technique influence on primary stability	2 [13,14]	ISQ differences at baseline; torque $\approx 24$ N·cm	Secondary stability equalized by 5 months; survival 100%	Early mechanical differences diminish during biological healing
Implant macrodesign (tissue vs bone level)	1 [11]	Torque $\approx 25$ –40 N·cm	100% survival at 12 months; lower marginal bone loss in tissue-level implants	Moderate torque sufficient; crestal bone remodeling influenced by design
Low torque threshold in atrophic maxilla	1 [12]	$>15$ N·cm (minimum required)	87.7% survival at 10 years; late failure 12.3%	Long-term success influenced more by biological and anatomical factors than torque alone
Moderate ISQ range in posterior maxilla	2 [10,13]	ISQ $\approx 55$ –65	Significant ISQ increase over 3–6 months; no early failures	Moderate initial stability adequate; secondary stability compensatory
Moderate torque range (general finding)	3 [11,12,14]	$\approx 20$ –35 N·cm	100% short- to medium-term survival; MBL generally $<0.6$ mm	No universal cut-off identified; moderate thresholds consistently successful

### 3.5 Synthesis of Results

Across the five included studies [10–14], mechanical stability thresholds demonstrated variable numerical ranges but consistently supported predictable osseointegration in posterior maxillary implants. Due to substantial heterogeneity in study design, surgical protocols, stability assessment methods (insertion torque vs. ISQ), outcome definitions (marginal bone loss, secondary stability, survival), and follow-up duration (5 months to 10 years), results were synthesized narratively rather than quantitatively.

Moderate primary stability levels were the most consistently associated with favorable outcomes. Insertion torque values typically ranged from approximately 20–35 N·cm [11,14], while baseline ISQ values were generally reported within the 55–65 range [10,13]. Across randomized and prospective studies, these stability levels were associated with 100% short- to medium-term implant survival and limited

marginal bone remodeling ( $<0.6$  mm at 12–28 months) [11,14].

Differences in surgical technique influenced primary stability [13], however, these differences diminished during healing, and secondary stability values converged over time [10,13].

In severely atrophic posterior maxillae, a lower torque threshold of  $>15$  N·cm was used as the minimum criterion for implant placement [12]. Although long-term survival remained relatively high (87.7% at 10 years), late implant failure was more strongly associated with peri-implant soft tissue conditions and sinus-related complications than with the initial mechanical stability threshold itself [12].

Implant macrodesign and surgical accuracy influenced peri-implant bone remodeling but did not alter short-term survival when moderate mechanical stability was achieved [11,14].

Overall, the synthesis suggests that no single universal mechanical stability cut-off

guaranteeing osseointegration can be defined. Rather, moderate primary stability (torque  $\geq 20$  N·cm or ISQ  $\geq 55$ ) appears sufficient for predictable osseointegration in posterior maxillary implants [10,11,13,14], while long-term outcomes are influenced by anatomical, biological, and surgical variables beyond the initial mechanical threshold [12].

Publication bias could not be formally assessed because fewer than 10 studies were included, making funnel plot-based methods unreliable. The certainty of evidence was not evaluated using the GRADE approach due to the small number and heterogeneity of the included studies.

#### 4. Discussion

Primary implant stability remains an important prerequisite for osseointegration because excessive micromotion at the bone-implant interface may impair bone healing. Experimental evidence indicates that micromovements exceeding approximately 50-150  $\mu\text{m}$  may promote fibrous tissue formation rather than bone integration [10–14]. These findings indicate that extremely high insertion torque values may not be necessary to achieve predictable osseointegration in posterior maxillary bone, which is typically characterized by lower density and anatomical constraints related to the maxillary sinus [15].

Primary implant stability remains an important prerequisite for osseointegration because excessive micromotion at the bone-implant interface may interfere with bone healing. Experimental studies have shown that micromovements exceeding approximately 50-150  $\mu\text{m}$  may promote fibrous tissue formation instead of bone integration [16]. Consequently, insertion torque and resonance frequency

analysis (RFA) are widely used to evaluate implant stability and monitor stability changes during healing [16,17]. Several clinical investigations have demonstrated a positive relationship between insertion torque and ISQ values, indicating that both parameters reflect the mechanical engagement between the implant and surrounding bone. For example, Sarfaraz et al. reported a significant correlation between insertion torque and RFA measurements, supporting their use as complementary indicators of implant stability during early healing [18].

The influence of surgical technique on primary stability has also been reported in the literature. Planinić et al. [13] observed higher initial ISQ values with the osteotome technique compared with conventional drilling and flapless placement; however, these differences disappeared during healing, suggesting that biological bone remodeling reduces early mechanical differences. Similar stability patterns have been described in studies evaluating different osteotomy techniques, where implants placed using various surgical approaches demonstrate comparable stability trajectories over time [19]. Yang and Geng [14] likewise reported comparable insertion torque values between navigation-assisted and freehand implant placement, with both approaches achieving 100% survival after approximately 28 months. Nevertheless, navigation-assisted placement resulted in lower marginal bone loss, indicating that surgical accuracy may contribute to improved peri-implant bone preservation even when primary stability values are similar.

Implant macrodesign may also influence peri-implant bone responses. Lombardi et al. [11] demonstrated a significant correlation between insertion torque and initial ISQ values and

reported lower marginal bone remodeling in tissue-level implants compared with bone-level designs. These findings suggest that implant design may influence peri-implant bone behavior even when implants are placed within similar mechanical stability ranges.

Evidence from severely atrophic posterior maxillae further indicates that relatively low stability thresholds may still be compatible with long-term implant success. Dung et al. [12] reported that implants placed with insertion torque values above 15 N·cm achieved a 10-year survival rate of 87.7%, despite challenging anatomical conditions. Importantly, implant failure was more strongly associated with biological factors such as insufficient keratinized tissue width, sinus membrane perforation, and poor oral hygiene than with the magnitude of the initial stability threshold. Similarly, clinical observations summarized in a study by Elian and Salem [20], reported successful osseointegration in implants placed with insertion torque values below 10 N·cm when implants were protected from functional loading during healing, suggesting that biological conditions may partially compensate for low mechanical stability.

Finally, several studies demonstrate that implant stability evolves during healing. Both Al-Hity et al. [10] and Planinić et al. [13] reported increases in ISQ values over time, reflecting the transition from primary mechanical stability to biologically mediated secondary stability. Similar stability progression patterns have been described in clinical investigations where ISQ values gradually increase during healing and reach a plateau within several weeks to months after implant placement [17,19].

Overall, the available evidence suggests that while adequate primary stability is necessary,

moderate mechanical stability levels appear sufficient for predictable osseointegration in posterior maxillary implants. Long-term success in this region appears to depend not only on mechanical stability but also on biological healing processes, implant design, and surgical accuracy. Future research should focus on establishing clearer stability thresholds and evaluating their interaction with bone quality, implant design, and surgical technique in the posterior maxilla.

## 5. Conclusions

Within the limitations of the available evidence, moderate primary mechanical stability appears sufficient to achieve predictable osseointegration in implants placed in the posterior maxilla. Across the included studies, insertion torque values ranging from >15 to approximately 40 N·cm and initial ISQ values around 55-65 were consistently associated with successful implant integration and high survival rates.

While surgical technique and implant macrodesign may influence early stability and peri-implant bone remodeling, long-term implant success appears to depend more strongly on biological factors and peri-implant conditions than on achieving extremely high primary stability values.

Overall, the findings suggest that adequate, rather than maximal, mechanical stability is sufficient for successful osseointegration in the posterior maxilla, provided that appropriate surgical planning and biological conditions are maintained.

## References

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