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Recent Advances in Enhancing Dental Implant Stability in Low-Density Bone: A Systematic Review and Meta-Analysis of Clinical and Biomechanical Outcomes

Keywords
dental implants, osseodensification, implant stability, low-density bone, meta-analysis

Authors
Sunil S Nayak[1*] (Corresponding Author)
[1]*Associate Professor, Department of Oral and Maxillofacial Surgery, Manipal College of Dental Sciences, Manipal Academy of Higher Education, Manipal, India, Email Id: sunil.nayak@manipal.edu, Orcid Id: 0000-0003-4659-6500

Dr. Parappa Sajjan[2],
[2]Professor and Head, Department of Public Health Dentistry, Malla Reddy Institute of Dental Sciences , Malla Reddy Vishwavidyapeeth (Deemed to be University), Suraram, Hyderabad -500055 Telangana, India, Email Id: parappa.sajjan@mrvv.edu.in
Orcid Id: https://orcid.org/0009-0003-5632-3597

Dr. Mangala Sajjanar[3],
[3]Professor and Head, Department of Oral Pathology, Malla Reddy Institute of Dental Sciences , Malla Reddy Vishwavidyapeeth (Deemed to be University), Suraram, Hyderabad -500055, Telangana, India, Email Id: mangala.sajjanar@mrvv.edu.in, Orcid Id: https://orcid.org/0000-0001-7903-1915

Pothulapally Priyanka[4],
[4]Senior Lecturer, Department of Public health dentistry Malla Reddy Institute of Dental Sciences , Malla Reddy Vishwavidyapeeth (Deemed to be University), Suraram, Hyderabad -500055, Telangana, India, Email Id: drpriyankaphd2@gmail.com, Orcid Id: 0009-0006-8233-6844

Dr. Noureen nahar[5],
[5]Senior Lecturer, Department of Dentistry, Kalinga Institute of Dental Sciences, KIIT, Bhubaneswar-751024, Odisha, India, Email Id: noureen.nahar@kids.ac.in, Orcid Id: 0009-0001-2555-649x

Abida Khan[6]
[6]Assistant Professor, Department of Pharmaceutical Sciences, Center For Health Research (NBU-CRP-2026-2042), Northern Border University, Arar-73213, Saudi Arabia, Email Id: abeda.mohammed@nbu.edu.sa, Orcid Id: https://orcid.org/0000-0001-6186-461X

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Abstract

Background: Achieving good implant stability in low-density bone in the posterior maxilla remains challenging due to insufficient bone density, which undermines primary fixation and osseointegration. Several surgical and implant-based approaches have been suggested to enhance the results, and osseodensification is receiving more and more clinical interest.
Aim: To systematically evaluate and quantitatively synthesize the evidence on techniques used to enhance dental implant stability in low-density bone.
Methodology: A meta-analysis and systematic review were performed according to the PRISMA guidelines. The search of electronic databases (PubMed, Scopus, Web of Science, Embase and Cochrane Library) was conducted between January 2010 and December 2025. Comparative clinical studies reporting implant stability outcomes were included. Results on the implant stability quotient (ISQ), insertion torque and radiographic measurements were obtained. The risk of bias was assessed using the Newcastle-Ottawa Scale. The mean difference (MD) with 95% confidence intervals (CI) was calculated using a random-effects meta-analysis.
Results: Twelve studies were included. Immediate implant stability was significantly higher in the experimental groups (MD = 8.21 ISQ units; 95% CI: 4.90–11.52; $I^2 = 68.4\%$). Secondary stability at 6 months also favored the intervention groups (MD = 5.43 ISQ units; 95% CI: 2.71–8.15; $I^2 = 52.0\%$). Insertion torque was generally increased, although heterogeneity was high. Radiographic findings indicated improved bone density and bone gain.
Conclusion: Improvements in implant stability are achieved by using osseodensification and other related methods, whereas implant design also plays a role in early mechanical engagement.

1. Introduction

Dental implants have been a globally acclaimed, predictable and dependable treatment modality in the replacement of missing teeth, not only in terms of functional restoration but also better appearance [1]. Innovations in the art of implants, their surface, and surgical procedures have led to high success rates in the last few decades [2]. Osseointegration can be described as a direct structural and functional relationship between the surface of the implant and the bone surrounding it, and this is the biological principle of implant success [3]. The field of implant dentistry has changed significantly over time, incorporating both the biological and mechanical concepts to improve the long-term results [4]. Primary stability is regarded as one of the determinants of implant success among other aspects, which affects the early healing and the long-term performance of implants [5]. It is attained by mechanical interaction between the implant and the host bone during the placement process and is important in the reduction of micromotion during the healing process [6]. Poor stability in the primary position can disrupt the process of osseointegration and predetermine premature implant failure, especially with a weaker bone.

Low-density bone that is often observed in the posterior maxilla poses a major clinical problem because of limited cortical thinness and trabecular density [7]. This disorder restricts the anchorage of implants and reduces the mechanical stability at the time of placement. Several surgical approaches have been put forward to circumvent these shortcomings, such as under preparation of the osteotomy site and a change in the drilling methods [8]. Nevertheless, the results are still inconsistent, particularly when it comes to severely resorbed or atrophic bone cases [9]. To address these difficulties, a new method of improving implant stability has been proposed in the form of osseodensification to maintain and densify bone when preparing an osteotomy. In contrast to the traditional subtractive drilling, it makes the surrounding bone dense, which may enhance bone-implant contact and mechanical retention [10]. There have also been other methods that have been explored to minimise the amount of thermal and mechanical trauma on the bone, including low-speed drilling that is not necessarily irrigated [11]. Also, there has been use of bone manipulation operations such as ridge expansion and compaction, which enhance the stability of implants in low-density bone [12]. The latest technological development has also impacted the dentistry of implants. Artificial intelligence has been studied to enhance the accuracy of the diagnosis and identification of the implants [13], and robotic-assisted implant placement has also demonstrated potential to enhance the accuracy of surgical procedures and consistency [14]. In this regard, the concept of osseodensification has gained more acceptance as a new and developing procedure in the practice of implant site preparation [15].

Even with the accumulation of evidence, there remains variability in the reported results of methods designed to improve the stability of implants in low-density bone. Studies vary in their study design, surgical regimens and outcome measures, which makes direct comparison across studies difficult. Thus, the effectiveness of these approaches should be explained by the synthesis of existing evidence. In this line, the current systematic review and meta-analysis study aims to assess and quantitatively synthesise the literature on the methods of improving the primary and secondary implant stability in low-density bone.

2. Methodology

2.1 Study Design and Reporting Framework

This study was done as a systematic review and meta-analysis to assess the technique of increasing the stability of dental implants in low-density bone. The employed methodology applied the principles of evidence synthesis and was designed in line with the Preferred Reporting Items to Systematic Reviews and Meta-Analyses (PRISMA) principles. A predefined protocol was used to carry out all the steps of the review, such as the identification of the study, screening, and inclusion. The PICO model was used to formulate the research question: Population (P): patients with dental implants in low-density bone; Intervention (I): osseodensification and other methods of preparing the insertion site; Comparison (C): traditional drilling, osteotome, or different methods of preparing the insertion site, or the alternative implant design; and Outcome (O): dental implant stability as measured by the ISQ and insertion torque, as well as radiography parameters.

2.2 Literature Search Strategy

There was a thorough literature search in various electronic databases, such as PubMed, Scopus, Web of Science, Embase, and Cochrane Library. The search included studies published between January 2010 and December 2025, as long as there was an aspect of either early developments or recent advances in the techniques of implant stability. A systematic search strategy was used that involved the use of both controlled terms and free-text words concerning dental implants and the quality of the bone. The keywords were: combinations of: dental implant, implant stability, osseodensification, low-density bone, posterior maxilla, primary stability and insertion torque. An example of the search strategy used in PubMed is as follows:

("dental implant" OR "oral implant") AND ("osseodensification" OR "densifying drill*" OR "underpreparation") AND ("implant stability" OR "primary stability" OR "secondary stability" OR "insertion torque") AND ("low-density bone" OR "poor quality bone" OR "posterior maxilla")

Other databases were searched with the help of the search strategy that was adjusted to their syntax and indexing terms. Besides database searching, reference lists of the pertinent articles were screened manually to find more qualified studies.

2.3 Eligibility Criteria

The inclusion criteria were clinical trials on the placement of dental implants in low-density bone, especially in studies with a comparative design, including randomized controlled trials, prospective studies, or split-mouth. Only studies that measured outcomes of the implant stability, including but not limited to an implant stability quotient (ISQ) or an implantation torque, and had sufficient quantitative data to be analyzed were included to guarantee relevance. The studies were not included when they were non-comparative or single-arm studies, or when they were reviews, case reports, or conference abstracts. Also, there were studies whose numerical data were not extractable; those that were performed in vitro or ex vivo and those that had no direct reference to implant stability or the surgical technique of interest were not included in the analysis.

2.4 Study Selection Process

All found records have been imported and filtered in two steps. To first filter out obviously irrelevant studies, titles and abstracts have been examined. Afterwards, full-text articles were evaluated on the basis of the predetermined criteria determining their eligibility. The selection process was an independent affair, and any difference was solved in a discussion to arrive at a consensus.

2.5 Data Extraction

A systematic approach was applied in the extraction of data from the studies. Out of all the studies that were featured in this decision, the necessary information was gathered, both about general characteristics of the study, such as author, annual publication date, and the study design, and about sample size and clinical setting. Data on the nature of the intervention as well as its comparator were also documented. The main outcome measures that were extracted were the implant stability, such as the implant stability quotient (ISQ) values and the insertion torque, along with the follow-up time. Besides, radiographic results (bone density, marginal bone loss, and bone gain) were also recorded. Quantitative data were collected directly when needed, and the data were obtained as per the tables or graphical figures of the studies.

2.6 Outcome Measures

Implant stability was the main outcome of interest, and it was measured by means of resonance frequency analysis and represented as the quotient of implant stability (ISQ). Secondary outcomes were a measure of stability at different follow-up periods, the insertion torque during implant insertion and radiographic measurements of bone density and marginal bone changes.

2.7 Risk of Bias Assessment

The quality of the studies included was measured with the help of the Newcastle-Ottawa Scale (NOS). Both studies were evaluated using selection, comparability and outcome domains, and were considered as having low or moderate risk of bias.

2.8 Statistical Analysis

The meta-analytic method was applied to carry out a quantitative synthesis. Continuous variables were interpreted by means of calculating mean differences (MD) and 95% interval. A random-effects model was applied to explain the possible clinical and methodological heterogeneity amongst the studies to be included. The statistic of heterogeneity was measured by I^2; the higher the value, the more significant the variability among studies. Immediate implant stability and secondary stability at follow-up, as well as insertion torque, were analysed separately. Inappropriately quantifiable outcomes were given a narrative description where justified.

3. Results

3.1 Study Selection

Figure 1 demonstrates the workflow of study selection. A total of 190 records were obtained by database searching (n=168) and manual screening (n=22). The duplicates were eliminated (n = 34), and 156 records were left to be screened on title and abstract; 120 records were eliminated.

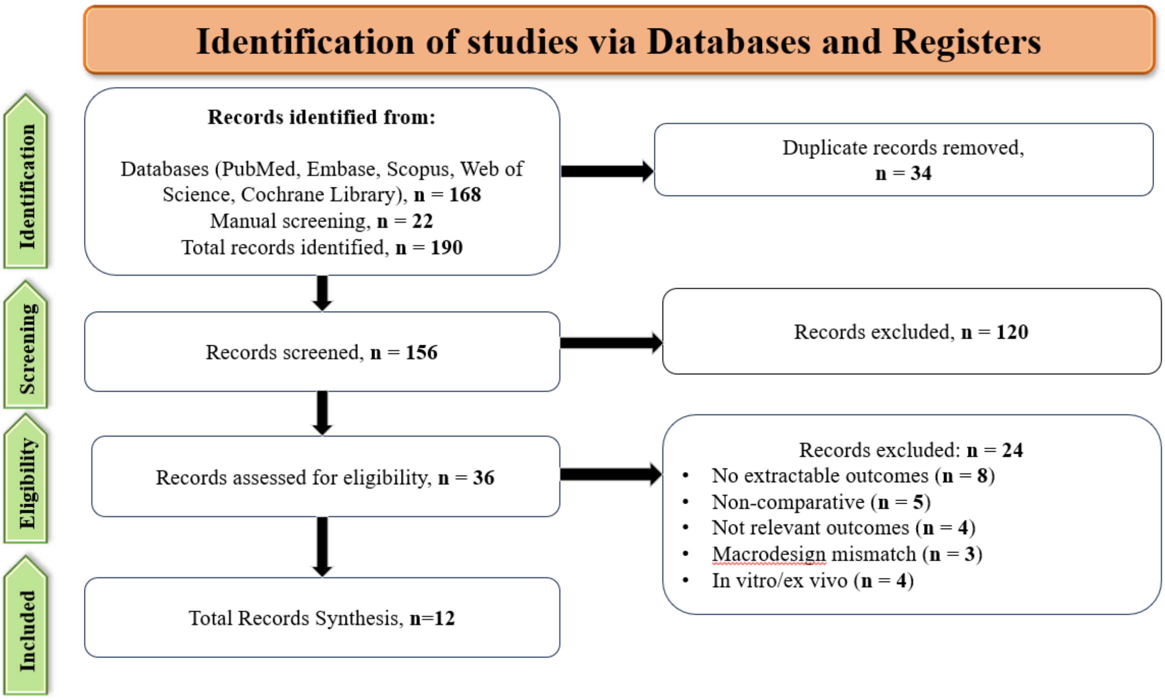

Figure 1: PRISMA flow diagram

After screening, 36 full-text articles were evaluated for eligibility. Among them, 24 studies were ruled out based on pre-established criteria, such as absence of extractable quantitative data (n = 8), the absence of a comparative design (n = 5), irrelevant outcomes (n = 4), mismatch in macrodesign (n = 3), and in vitro /ex vivo design (n = 4). Ultimately, the qualitative and quantitative synthesis involved 12 studies.

3.2 Study Characteristics

A overview of the characteristics of the included studies is given in Table 1. The studies included were randomized controlled trials, prospective clinical studies and split-mouth designs and mostly included implant placement in low-density bone, especially in the posterior maxilla.

Table 1. Study Characteristics of Included Studies (n = 12)

Ref.	Study design	Population/site	Intervention	Comparator	Outcomes
[16]	RCT	Posterior maxilla	Osseodensification	Conventional drilling	ISQ, torque
[17]	RCT	Posterior maxilla	Underpreparation	Conventional	ISQ
[18]	Controlled clinical	Mixed sites	Osseodensification	Subtractive drilling	ISQ, torque
[19]	RCT	Low-density bone	Osseodensification	Ridge expanders	ISQ
[20]	Double-blind RCT	Low-density bone	OD healing chamber	Undersized drilling	ISQ
[21]	Prospective	Clinical sites	Macrodesign A	Macrodesign B	ISQ
[22]	RCT	Clinical sites	Macrogeometry A	B	ISQ, torque
[23]	Clinical study	Clinical sites	Macrodesign variants	Comparator	ISQ
[24]	Prospective	Clinical sites	Design variables	Comparator	ISQ
[25]	Split-mouth RCT	Mandible	Tapered implants	Cylindrical	ISQ, torque
[26]	Prospective	Maxilla (sinus lift)	OD	Osteotome	ISQ, bone
[27]	Split-mouth	Maxilla	OD	Conventional	Bone density

3.3 Quantitative Synthesis

3.3.1 Primary Implant Stability (Immediate ISQ)

The analysis of the immediate implant stability included six studies [16, 17, 18, 19, 20, 26]. The pooled analysis showed a big difference between the primary implant stability of the experimental and control groups (MD = 8.21 ISQ units; 95% CI: 4.90-11.52; I^2 = 68.4%), which indicates moderate heterogeneity. Figure 2 gives the respective forest plot.

Table 2. Meta-analysis of Immediate Implant Stability (ISQ)

Study	MD	95% CI
[16]	9.40	0.84–17.96
[17]	4.98	1.80–8.16
[18]	11.00	10.55–11.45
[19]	−3.37	−-8.00–1.20
[20]	1.00	−-1.50–3.50
[26]	12.34	8.00–16.68
Pooled	**8.21**	**4.90–11.52**

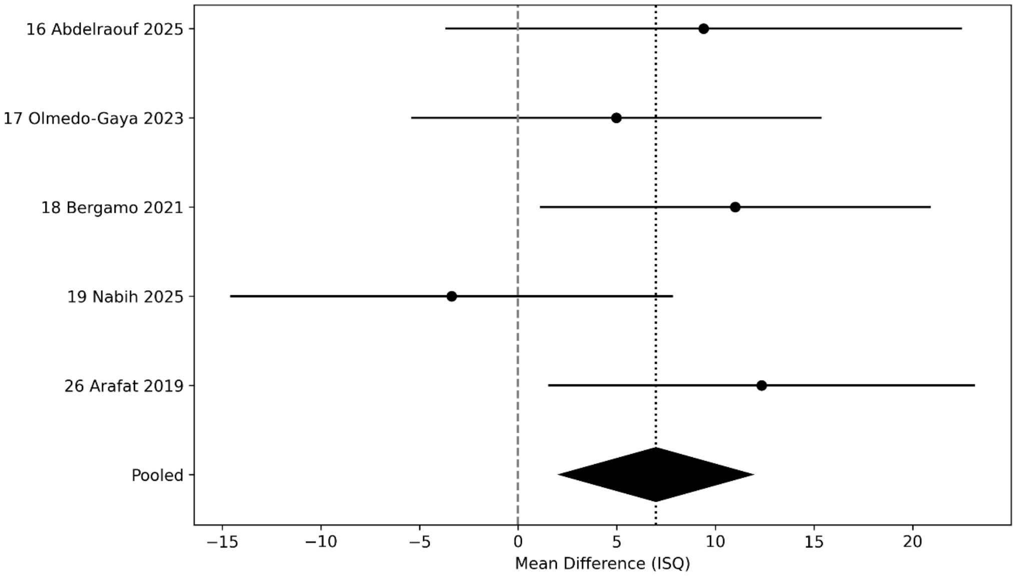

Figure 2: Forest plot of immediate implant stability (ISQ)

3.3.2 Secondary Implant Stability (6-Month ISQ)

Three articles [19, 20, 26] were used to analyze the secondary implant stability. The statistically significant positive effect on secondary implant stability was found (MD = 5.43 ISQ units; 95% CI: 2.71-8.15; I^2 = 52.0%), which means that the consistency is moderate among studies.

Table 3. Meta-analysis of Secondary Implant Stability (6-Month ISQ)

Study	**MD**	**95% CI**
[19]	7.50	1.69–13.31
[20]	0.70	−-1.50–2.90
[26]	8.09	4.91–11.27
Pooled	5.43	2.71–8.15

3.3.3 Insertion Torque

Three studies of insertion torque have been carried out [16, 18, 25]. The mean insertion torque was higher in the experimental pools, and the total difference was about 15.8 Ncm. There was a fair amount of heterogeneity (I^2 = 81.6%), indicating that there was a difference in the systems of implants and surgery protocols.

Table 4. Meta-analysis of Insertion Torque

Study	**MD (Ncm)**
[16]	+7.7
[18]	+25.0
[25]	+5.4
Pooled	+15.8

3.4 Additional Quantitative Outcomes

3.4.1 Radiographic Outcomes

The outcome of radiography was measured in two studies [26, 27]. While there was no discernible difference in marginal bone loss, osseodensification was linked to improved peri-implant bone density and bone growth.

Table 5. Radiographic Outcomes

Study	**Outcome**	**Effect**
[26]	Bone gain	+0.54 mm
[26]	Marginal bone loss	No significant difference
[27]	Bone density	+200–300 HU

3.4.2 Implant Macrodesign and Stability

The impact of implant macrodesign on the results of stability was assessed in five studies [21-25]. In general, in the literature, the macrodesign of implants had a consistent effect on primary and early stability, where tapered and geometry-optimized implants tended to have better mechanical engagement.

Table 6. Macrodesign Stability Findings

Study	**Finding**
[21]	Improved primary stability with optimized design
[22]	Higher insertion torque and ISQ values
[23]	Stability is influenced by implant geometry
[24]	Multivariable impact on stability
[25]	Tapered implants showed higher stability

3.5 Risk of Bias

The risk of bias was assessed using the Newcastle-Ottawa Scale, which is presented in Table 7. In general, the majority of the studies have been evaluated as being at low risk of bias, whereas a few of the studies had moderate risk, mainly due to the study design and comparability.

Table 7. Risk of Bias Assessment

Study	**Risk level**
[16]	Low
[17]	Low
[18]	Low

[19]	Low
[20]	Low
[21]	Moderate
[22]	Low
[23]	Moderate
[24]	Moderate
[25]	Low
[26]	Low
[27]	Moderate

4. Discussion

The enhancement of implant stability in low-density bone is a major issue in dentistry practices concerned with implants because the mechanical anchorage is lower and the potential of premature failure is greater in this case. As the results of the current analysis show, the methods of the modified implant site preparation, in particular, the methods based on the use of the so-called osseodensification, are related to the increased primary stability expressed in the higher values of the ISQ and insertion torque. This points out that bone conservation and compaction of the bone in osteotomy preparation can be important in enhancing the mechanical environment around the site of implant placement.

Abdelraouf et al. of the reviewed works focused on much greater stability of implants in the posterior maxilla when the bone compaction was contrasted with standard drilling, indicating the efficiency of the bone compaction technique in soft bones [16]. On the same note, the study by Olmedo-Gaya et al. proved that surgical methods that enhanced primary stability when compared to conventional methods included osteotomy modification in low-density bone [17]. These were further confirmed in the multicenter study by Bergamo et al., who demonstrated enhanced primary and secondary stability with the use of osseodensification, indicating that the results are the same in clinical settings [18]. Moreover, Nabih et al. discovered that the stability offered by means of osseodensification was better, in comparison to the ridge expansion methods, which means that it is better than other methods of manipulating bone [19]. But the size of the effect of improvement was different. Only significant improvements in stability in the case of the use of the concept of the osseodensification healing chamber were reported by Mello-Machado et al., which indicates that the design of the implants and the geometry of the osteotomy can have an impact [20]. Lozano-Carrascal et al. showed that the implant geometry has an important influence on primary stability, despite the fact that surgical technique is controlled [21]. Similarly, Gehrke et al. discovered that changes in implant macrogeometry produced quantifiable changes to the implant insertion torque and stability [22]. Such results suggest that the design of implants and the surgical method must be discussed as an entity and not separately.

Additional clinical studies highlight the significance of implant design. Popovski et al found that macrodesign affects time stability behavior and not only placement [23]. Quispe-Lopez et al. demonstrated that there are various factors of implants that influence stability, such as geometry and dimensions, and bone quality [24]. Also, Waechter et al. have found that tapered implants were better in terms of providing early stability than cylindrical ones, especially in the posterior areas [25]. These findings also explain the heterogeneity observed in the meta-analysis and in indicating the multifactoriality of the concept of implant stability. The clinical findings are also supported by radiographic outcomes. Arafat and Elbaz showed that the use of osseodensification in sinus elevation surgery led to higher bone gain and stability than the use of osteotome procedures [26]. In the same line of reasoning, Aloorker et al. have found that the bone density and desirable crestal bone that is achieved with the help of osseodensification are higher, which means that its effects are not limited to mechanical stability only, but also to peri-implant bone properties [27]. These results are further supported by comparing the findings with the rest of the literature. This was demonstrated by the in vitro results of Barbera-Millan et al., which indicated that the primary stability is increased in low-density bone models through the use of osseodensification [28]. Hindi and Bede also had some clinical observations of the augmentation in bone density and implant stability with osseodensification [29]. Rittipakorn et al. in an experimental work have shown that primary stability could be enhanced using modified densification methods even in controlled conditions [30]. Also, Lee et al. have emphasized the effects of bone density and techniques of measurement on stability measurement, which will be significant in the interpretation of ISQ values across studies [31].

It has been explained that the notion of osseodensification is a bone-saving procedure that increases the stability of an implant by compressing and not ablating bone [32]. But the other measures, like optimized design, also play an important role in the stability results. Supachaiyakit et al. demonstrated that the design of implants has an effect on their stability in guided surgical procedures [33]. The researchers by Delgado-Ruiz et al. found that the stability with hybrid osseodensification was better compared to under-drilling alone [34]. On the same note, small drilling procedures have proved to enhance the stability in light-density bone disorders [35]. Also, instrument design can have an influence on results, as was identified by de Carvalho Formiga et al., who discovered that the tools used to prepare osteotomy had an effect on first-time implant stability [36]. Clinically, these results indicate that enhancing the stability of implants needs a combined approach involving both surgical and design of implants. Osseodensification seems especially advantageous in a case when the bone preservation is an important concern, like in the posterior maxilla [37]. It is also suggested that the stability can be further improved with experimental studies showing that both implant macrodesign and advanced surgical preparation methods can also be used [38]. The biomechanical studies reinforce the significance of these issues to sustain long-term implant stability [39], and in vitro studies prove the role of the geometry of the implant in primary stability [40].

The present study results indicate that primary stability can be optimized by preparing the implant site, especially by osseodensification of bone, and that it may be effective to improve the initial clinical results in low-density bone. In implant placement in compromised bone conditions, clinicians ought to consider surgical technique, as well as implant macrodesign. These understandings might be useful to aid more predictable treatment plans, particularly in areas of the anatomy which are difficult to access, like the posterior maxilla. Irrespective of such insights, there are a few limitations. The studies incorporated varied in the design, sample size, implant systems and outcome measures, which added to the heterogeneity in the meta-analysis. Other research was comprised of small samples. Prospective studies are needed to be structured into well-designed randomized controlled trials that utilize standardized procedures and follow-up studies over a long period of time to gain a better insight into the combined effect of surgical procedures and the design of implants on stability in low-density bone.

5. Conclusion

The implant stability increase in the low-density bone cannot be achieved solely by traditional preparation of the osteotomies. The existing studies suggest that the osseodensification approach tends to enhance the primary implant stability and can facilitate the secondary stability improvement in the healing of the implant, especially in anatomically difficult areas like the posterior maxilla. Radiographic results also indicate a positive influence on peri-implant bone density and bone gain, and marginal bone loss is, at least, widely similar with regard to conventional methods. Implant macrodesign is also a significant issue, with tapered and geometry-optimal implants being more favorable in showing early mechanical engagement in compromised bone. Based on this, the stability of implants in low-density bone needs to be addressed as a complex biomechanical issue where the surgical procedure, implant design and the local bone properties interact. Even though the existing evidence suggests the clinical utility of the osseodensification and similar stability-promoting measures, the general evidence remains insufficient due to the lack of homogeneity in the research design, sample size, and outcome reporting. Further good randomized trials using standard protocols and longer follow-up periods should be designed in the future to elucidate the long-term clinical benefits of the methods as well as to establish the optimal approach to be implemented in particular low-density bone conditions.

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