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Original Article

Influence of Tapered vs. Cylindrical Zirconia Implant Macrogeometry on Primary Stability Across Simulated Bone Densities: An In Vitro Resonance Frequency Analysis

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ABSTRACT

Titanium implants have long been established as reliable in dental implantology; however, zirconia implants are now being explored as a metal-free substitute. This investigation assessed how zirconia implant macrodesign and bone density influence initial implant stability. Two zirconia systems—Neodent® Zi Ceramic and Straumann® PURE Ceramic—were evaluated using polyurethane blocks simulating varying bone densities (10, 15, 20, 30, and 40 PCF). Each implant type underwent repeated insertion and removal. Resonance frequency analysis (RFA) was performed using the Osstell® Beacon to record stability. Statistical evaluation included the Shapiro–Wilk, t-test, Mann–Whitney U, and Kruskal–Wallis tests, with $p < 0.05$ considered significant.

The tapered Neodent® Zi Ceramic Implant produced consistently higher ISQ readings across all densities than the Straumann® PURE Ceramic Implant ($p = 0.035$). Moreover, reduced foam density was linked to lower stability outcomes ($p < 0.05$). The findings demonstrate that both implant macrogeometry and bone quality have a substantial effect on primary stability. Tapered implants achieved superior initial fixation compared with cylindrical ones, emphasizing the need to consider design configuration and bone density when optimizing implant stability in practice.

Keywords: Zirconia, Dental implant, Bone density, RFA, Primary stability

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Introduction

For several decades, titanium has served as the principal biomaterial for dental implants and is still considered the benchmark material in modern implantology [1]. Studies consistently report over 95% survival after ten years [1–4].

Despite its success, extensive research on titanium implants has revealed certain disadvantages, including aesthetic limitations in visible regions and adverse tissue reactions in sites with gingival thickness under 2 mm [1, 5, 6]. Titanium can trigger Type IV hypersensitivity [7, 8], involving T-lymphocyte activation and chronic inflammation, potentially leading to peri-implant tissue loss [8]. Microparticles and ions originating from titanium have been identified in peri-implant soft tissue, bone, and lymph nodes [5, 6, 9]. These contaminants can stimulate the secretion of pro-inflammatory markers—such as TNF-α, IL-1β, and RANK-L—which contribute to bone resorption and peri-implantitis development [10].

Conversely, zirconia has gained recognition as an aesthetic and biologically compatible option because of its high strength, corrosion resistance, and natural tooth-like color [6, 8, 9, 11, 12]. This material performs particularly well in esthetic regions, such as the anterior mandible, where thin mucosal tissues are common

[13]. Zirconia abutments enhance soft-tissue color blending with surrounding dentition and have demonstrated Pink Esthetic Score, White Esthetic Score, and Peri-Implant and Crown Index values that surpass clinical acceptability criteria [14].

Unlike titanium, zirconia does not induce cytotoxic or inflammatory effects, nor does it release metal ions or provoke arachidonic acid metabolism [15]. Therefore, it is often indicated for patients exhibiting metal intolerance or titanium hypersensitivity [12, 16]. Its low surface energy discourages the adhesion of periodontal pathogens, resulting in reduced bacterial colonization and a lower incidence of peri-mucositis [1, 11–13, 16, 17]. Studies have shown that Bone-to-Implant Contact (BIC) for zirconia implants is comparable to titanium, and modified surfaces may even reduce early failure risk [6].

According to meta-analytical data, zirconia implants display 1- and 2-year survival rates of 98.3% and 97.2%, respectively, with mean marginal bone loss around 0.7 mm after one year [18]. Longitudinal studies report survival of 97.5% [19] and 98.5% [20] at 3 years, and 98.4% at 5 years [21].

Osseointegration represents a progressive transition in which mechanical fixation (primary stability) is gradually replaced by biological anchorage (secondary stability). Initially, primary stability arises from direct mechanical contact between implant surfaces and bone walls and is influenced by macro- and microgeometry, bone density, osteotomy design, and implant position relative to the crestal bone.

Subsequently, secondary stability develops through new bone formation and remodeling, starting with osteoblastic deposition on the implant surface [22].

The structural design of an implant plays a key role in ensuring long-term osseointegration and maintaining stability. Several macrogeometric variables—including taper, diameter, thread profile, length, and surface roughness—affect mechanical engagement [23]. Conical implants are particularly effective in low-density bone, enhancing primary fixation through bone compression and even load distribution in the cortical zone [23, 24]. They also minimize the risk of buccal or lingual perforation in areas with bone concavity and are advantageous when the alveolar crest is narrow, facilitating safe implant positioning between adjacent roots [24, 25].

Implant stability represents a key parameter throughout the stages of dental rehabilitation, as it enables clinicians to forecast early implant loss, evaluate osseointegration quality, and determine suitability for immediate loading [26]. Among existing assessment techniques, resonance frequency analysis (RFA) is regarded as a noninvasive, precise, and reproducible approach for measuring implant anchorage [27].

This method operates by detecting resonant vibrations that typically range from 3000 to 8500 Hz, which correspond to the level of fixation and integration between the implant and its surrounding bone, independent of when the measurement occurs [27, 28]. The most commonly adopted device for this purpose is the Osstell® system, which is portable, wireless, and easy to use [26]. A SmartPeg™ transducer is attached to the implant, and when subjected to magnetic pulses from the Osstell® probe, it begins to oscillate. The resulting vibration frequency is converted into an Implant Stability Quotient (ISQ) on a 0–100 scale [28]. The latest generation, Osstell® Beacon, simplifies data collection by taking two readings—one in the mesio-distal direction and another bucco-lingually—while positioning the probe 2–4 mm from the SmartPeg™ at roughly a 45° angle, ensuring no physical contact [29]. ISQ results are interpreted as follows: >70 denotes high stability, 60–69 indicates moderate stability, and <60 reflects low stability [30]. While multiple biological and mechanical parameters may influence primary fixation, RFA remains the most dependable in vivo method for quantifying this property [26].

The purpose of the present in vitro investigation was to compare the initial stability of two zirconia implant systems with distinct macrogeometric designs using RFA and to explore how bone density impacts these measurements. This work is particularly relevant since zirconia is increasingly considered a nonmetallic substitute for titanium, though scientific validation of its mechanical behavior remains incomplete. Because implant geometry and zirconia's intrinsic characteristics both influence stability, examining these variables provides insight into long-term osseointegration success.

Two hypotheses guided the study:

- For implant geometry, the null hypothesis (H_0) predicted no meaningful variation in primary stability between designs, whereas the alternative hypothesis (H_1) suggested a significant difference.
- For bone density, the null hypothesis (H_0) proposed no difference in stability across densities, while the alternative (H_1) indicated significant variation among them.

Validating or rejecting these assumptions helps clarify how design configuration and bone quality influence the achievement of optimal primary anchorage, thus offering guidance for the clinical application of zirconia implants.

Materials and Methods

Implant systems and synthetic bone models

Two zirconia implant types from different producers, each with specific macrodesigns, were analyzed **(Figure 1)**.

The Neodent® Zi Ceramic Implant (Neodent, Curitiba, Brazil) is made from yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) and features a tapered design with dual trapezoidal threads. It measures 4.3 mm in diameter and 11.5 mm in length, has a white finish, and utilizes the ZiLock® connection. Its surface undergoes Neoporos® treatment.

The Straumann® PURE Ceramic Implant (Institut Straumann AG, Basel, Switzerland) is likewise composed of Y-TZP zirconia, but designed as a two-part cylindrical, tissue-level system. It has a 4.1 mm endosteal diameter, a 12 mm length, an ivory color, and an internal regular-diameter connection, with a ZLA® surface modification (Institut Straumann AG, Basel, Switzerland).

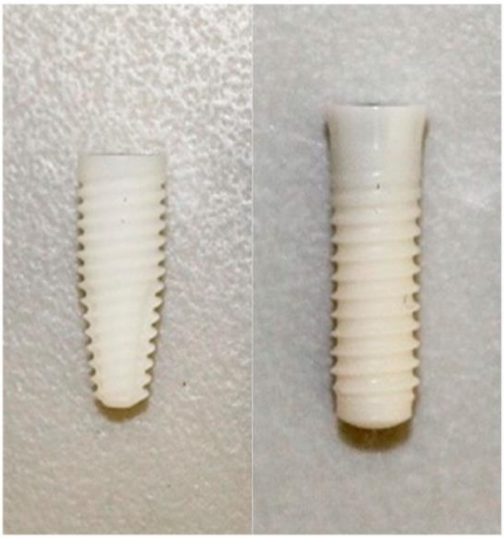


Figure 1. Neodent® Zi Ceramic Implant and Straumann® PURE Ceramic Implant.

A single polyurethane model (Nacional Ossos®, Ref. 12458, Jaú, São Paulo, Brazil) containing five regions of differing densities—without cortical structure—was used to simulate bone **(Figure 2)**. The overall block measured 225 × 45 × 25 mm, with each density segment sized 45 × 45 × 25 mm.

Figure 2. Nacional Ossos® polyurethane foam block.

The color-coded density sections were:

- Block 1: 10 PCF (0.16 g/cm³), light green
- Block 2: 15 PCF (0.24 g/cm³), pink
- Block 3: 20 PCF (0.32 g/cm³), light orange
- Block 4: 30 PCF (0.48 g/cm³), dark orange
- Block 5: 40 PCF (0.96 g/cm³), brown

As specified by the manufacturer, these densities correspond to simulated bone types as follows: 40 PCF → Type I, 30 PCF → Type II, 20 PCF → between Types II and III, 15 PCF → Type III, and 10 PCF → Type IV.

Sample description

This research analyzed a total of 90 implant placements, including 50 Straumann® Pure Ceramic Implants (Institut Straumann AG, Basel, Switzerland) and 40 Neodent® Zi Ceramic Implants (Neodent, Curitiba, Brazil). The Neodent® system follows a brand-specific protocol adapted for four distinct bone categories (I–IV). Therefore, implantation at a 20 PCF density was excluded from the procedure.

Drilling and insertion protocols

Before the osteotomy phase, a paper template was produced to identify drilling sites, maintaining a minimum spacing of 3 mm between implants in accordance with the manufacturer's guidance **(Figure 3)**. The complete methodology is outlined in the flow diagram **(Figure 4)**.

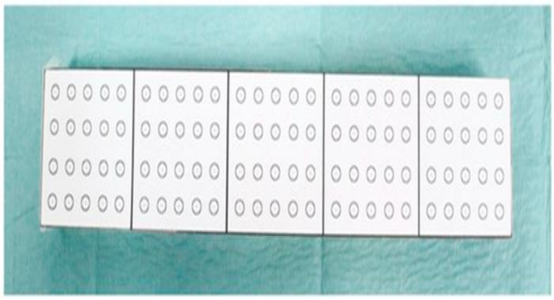


Figure 3. Paper guide showing selected osteotomy locations.

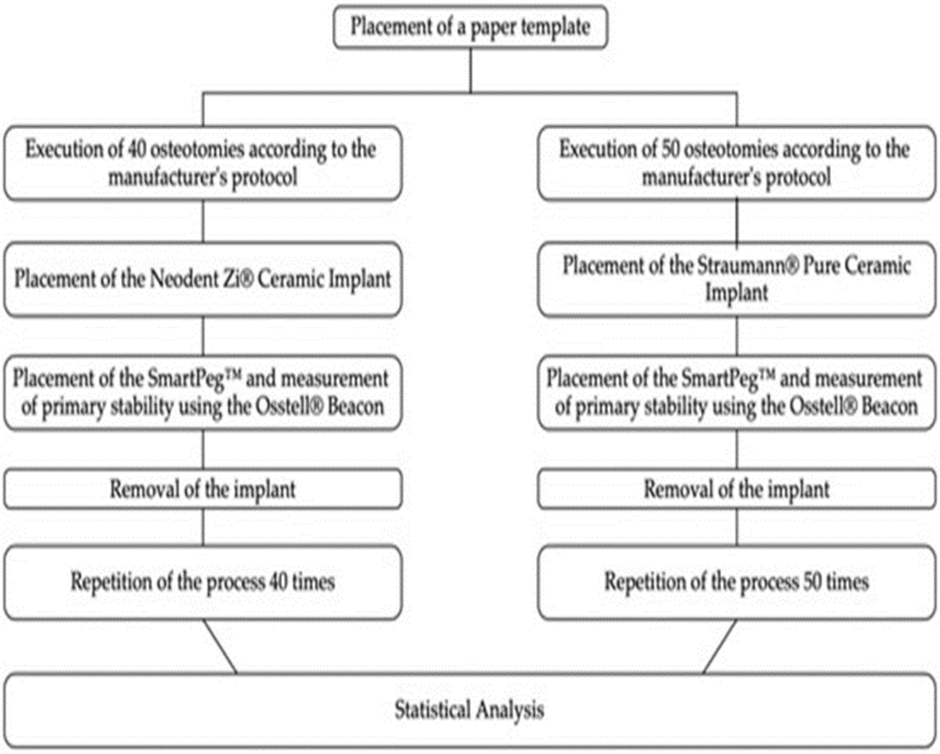
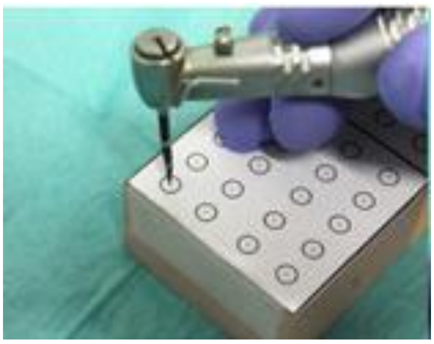


Figure 4. Overview of the experimental workflow.

For Neodent Zi® Ceramic Implant placements (Neodent, Curitiba, Brazil), the yellow-coded Neodent® surgical kit was employed **(Figures 5 and 6)**.

Figure 5. Drilling order per Neodent® protocol.



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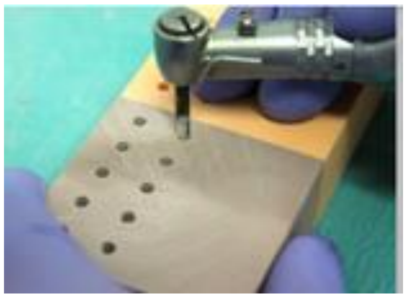

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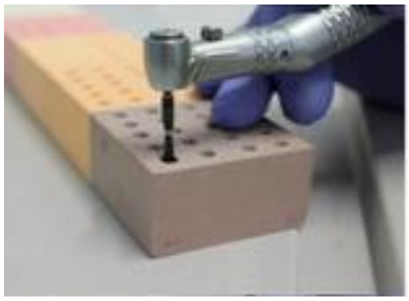

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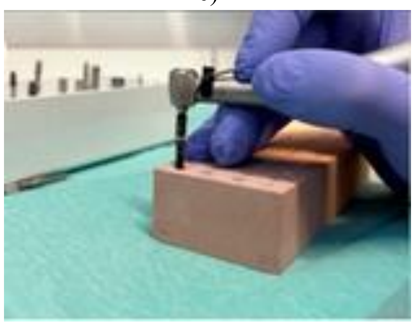

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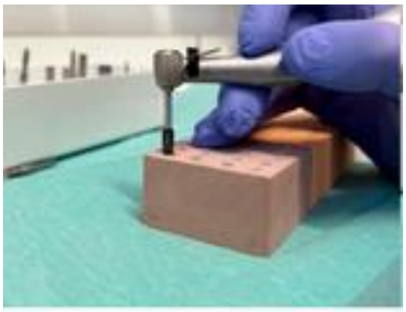

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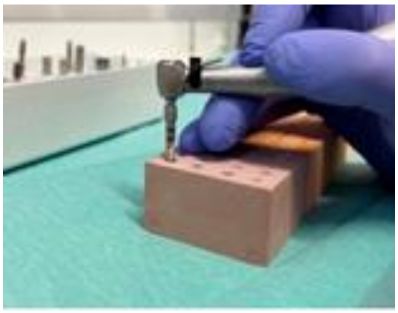

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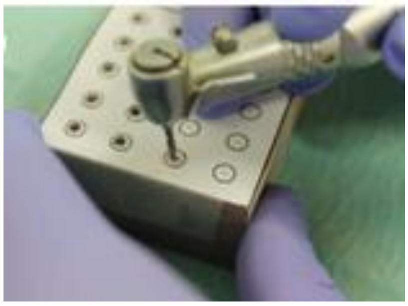
Figure 6. Sequence of implant site preparation: (a) Initial Needle Drill, (b) Tapered Drill Ø 2.0 mm, (c) Tapered Drill Ø 3.5 mm, (d) Tapered Drill Ø 4.3 mm, (e) Countersink Drill Ø 4.3 mm, (f) Bone Tap Ø 4.3 mm.

- Initial Needle Drill — 1200 rpm
- Tapered Drill Ø 2.0 mm — 1200 rpm
- Tapered Drill Ø 3.5 mm — 1200 rpm
- Tapered Drill Ø 4.3 mm — 1200 rpm
- Countersink Drill Ø 4.3 mm (type III bone) — 300 rpm
- Bone Tap Ø 4.3 mm (type I and II bone) — 30 rpm

For the Straumann® Pure Ceramic Implant (Institut Straumann AG, Basel, Switzerland), the corresponding Straumann® surgical kit was applied **(Figures 7 and 8)**.

Figure 7. Drill sequence for Straumann® protocol.



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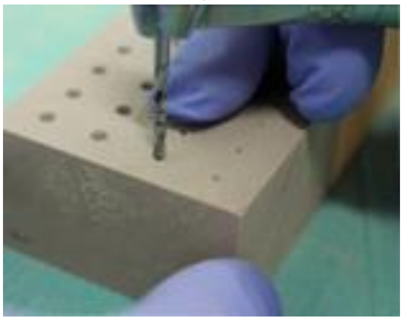

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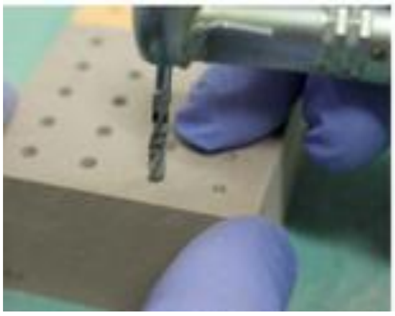

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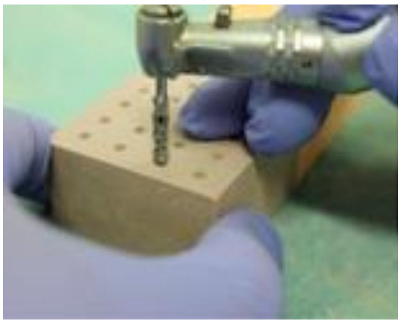

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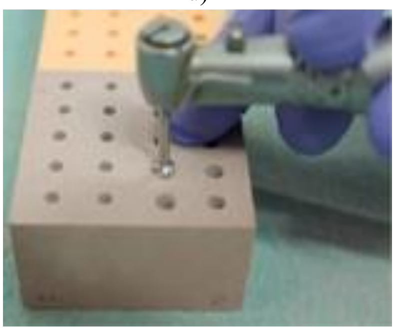

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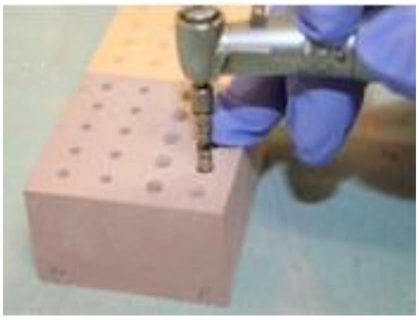

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Figure 8. Implant site preparation sequence: (a) Needle Drill Ø 1.6 mm, (b) Pilot Drill 1 Ø 2.2 mm, (c) Pilot Drill 2 Ø 2.8 mm, (d) Twist Drill PRO Ø 3.5 mm, (e) BL Profile Drill Ø 4.1 mm, (f) BL Tap for Adapter Ø 4.1 mm.

- Needle Drill Ø 1.6 mm — 800 rpm
- Pilot Drill 1 Ø 2.2 mm — 800 rpm
- Pilot Drill 2 Ø 2.8 mm — 600 rpm
- Twist Drill PRO Ø 3.5 mm — 500 rpm
- BL Profile Drill Ø 4.1 mm — 300 rpm
- BL Tap for Adapter Ø 4.1 mm (type I bone) — 300 rpm

The polyurethane foam block in **Figure 9** illustrates the drilled sites: the first and second rows correspond to 40 osteotomies for the Neodent® Zi implants, while the third and fourth rows represent 50 osteotomies for the Straumann® Pure Ceramic implants.

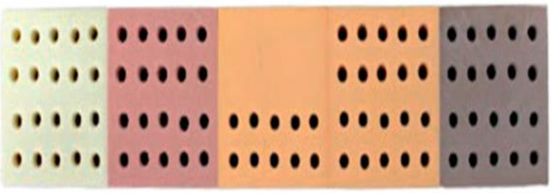
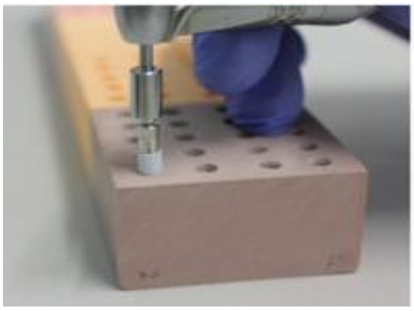


Figure 9. Polyurethane block following osteotomy preparation.

Following site preparation, Neodent® Zi Ceramic Implants were inserted at 30 rpm with a torque of 35 N/cm **(Figure 10a)**, whereas Straumann® Pure Ceramic Implants were placed at 15 rpm with the same torque **(Figure 10b)**. All procedures were executed by Master's students in Dental Medicine under the supervision of an experienced oral surgeon.



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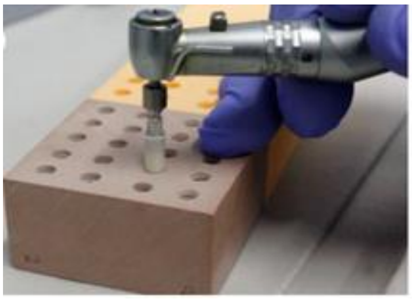


b)

Figure 10. (a) Insertion of Neodent® Zi Implant; (b) Insertion of Straumann® Pure Ceramic Implant.

Implant stability measurement

Primary stability was evaluated through Resonance Frequency Analysis (RFA) using the Osstell® Beacon (Osstell, Gothenburg, Sweden).

For Straumann® implants, SmartPeg™ type 81 (ref. 100671) was used, and for Neodent® implants, SmartPeg™ type 99 (ref. 100764) was employed. Each SmartPeg™ was manually attached, and the probe was positioned 2–4 mm from the peg at an approximate 45° angle, avoiding contact.

Measurements were recorded three times in two orientations (mesio-distal and vestibulo-lingual), and the average ISQ was calculated for each sample. Following assessment, implants were removed using reverse torque equal to the insertion torque.

Statistical evaluation

Data collected via the Osstell® device were analyzed using SPSS v.28 (SPSS Inc., Chicago, IL, USA). The objective was to assess both inter-group and intra-group variations across five bone density levels, determining how implant macrodesign and bone type affected ISQ outcomes.

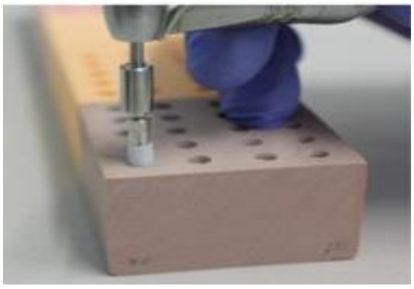
Depending on distribution and variance, different statistical methods were applied: Shapiro–Wilk test, t-test, Mann–Whitney U test, and Kruskal–Wallis test.

- t-tests were used for two normally distributed groups.
- Mann–Whitney U tests were applied when distributions were non-normal.

- Kruskal–Wallis tests handled three or more groups with non-homogeneous variances. A significance threshold of 5% ($p < 0.05$) was used for all tests.

Results and Discussion

Impact of implant macrogeometry on initial anchorage
A total of 90 implants were positioned for analysis, including 40 Neodent® and 50 Straumann® devices. The Neodent® implants presented an average ISQ of 65.54 ± 9.12, whereas the Straumann® models achieved 61.66 ± 10.62 **(Figure 11)**. Despite the absence of normal data distribution, the sample size ($n \geq 30$) justified performing a t-test to compare means. The 95% confidence limits (−3.319352 to 8.086952) crossed zero, indicating an inconclusive mean difference. However, the positive deviation (3.877500 > 0) combined with a significant p-value ($p = 0.035$) supports that the Neodent® Zi Ceramic Implant (Neodent, Curitiba, Brazil) recorded higher resonance frequency stability than the Straumann® Pure Ceramic Implant (Institut Straumann AB, Basel, Switzerland).



a)

b)

Figure 11. Mean ISQ distribution.

Table 1 outlines the mean ISQ readings, standard deviations, and corresponding p-values for each implant at different simulated bone densities. At 10 PCF, a significant difference ($p < 0.05$) was evident, favoring the Neodent® design, as depicted in **Figure 12**. The same pattern emerged at 15 PCF ($p = 0.001$), 30 PCF ($p < 0.05$), and 40 PCF ($p = 0.048$), confirming that the Neodent® implant consistently achieved greater primary stability.

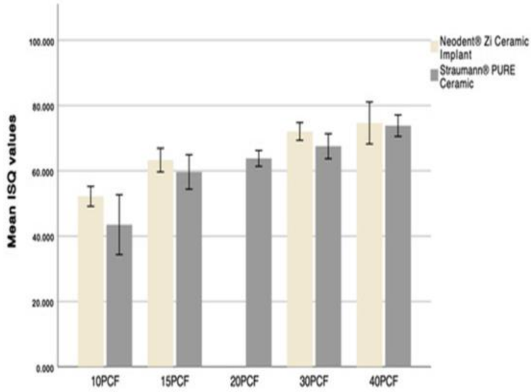


Figure 12. Average ISQ across bone densities and implant types.

Table 1. Mean ISQ, standard deviation, and significance by implant and bone density.

Bone Density (PCF)	Neodent® (Mean ± SD)	Straumann® (Mean ± SD)	p-Value
10 PCF	52.18 ± 1.52	43.50 ± 4.58	< 0.001
15 PCF	63.28 ± 1.81	59.65 ± 2.64	0.001
20 PCF	—	63.80 ± 1.21	—
30 PCF	72.05 ± 1.36	67.53 ± 1.91	< 0.001
40 PCF	74.63 ± 3.21	73.82 ± 1.64	0.048

Straumann® implant performance across varying densities
Significant changes in ISQ scores were observed when bone density varied ($p < 0.05$). The pairwise comparison results **(Table 2)** demonstrated that 10 PCF exhibited lower primary stability than 20 PCF ($p < 0.05$), 30 PCF ($p < 0.05$), and 40 PCF ($p < 0.05$). Additionally, stability at 15 PCF was inferior to 30 PCF ($p < 0.05$) and 40 PCF ($p < 0.05$), while 20 PCF remained lower than 40 PCF ($p < 0.05$).

Table 2. Pairwise statistical comparison for Straumann® Pure Ceramic Implant (Institut Straumann AB, Basel, Switzerland) across bone densities.

Density Comparison	p-Value	Adjusted p-Value*
10 PCF – 15 PCF	0.104	1.000

10 PCF – 20 PCF	0.002	0.024
10 PCF – 30 PCF	< 0.001	0.000
10 PCF – 40 PCF	< 0.001	0.000
15 PCF – 20 PCF	0.158	1.000
15 PCF – 30 PCF	0.004	0.036
15 PCF – 40 PCF	< 0.001	0.000
20 PCF – 30 PCF	0.133	1.000
20 PCF – 40 PCF	0.002	0.019
30 PCF – 40 PCF	0.111	1.000

Note: Bonferroni adjustment applied for multiple comparisons.

Neodent® implant stability at distinct bone densities

For the Neodent® implant system, ISQ outcomes also showed significant variation across the evaluated densities ($p < 0.05$). As displayed in **Table 3**, anchorage at 10 PCF was significantly weaker compared with 30 PCF ($p < 0.05$) and 40 PCF ($p < 0.05$). Moreover, 15 PCF demonstrated lower stability than 40 PCF ($p < 0.05$).

Table 3. Pairwise statistical analysis for Neodent® Zi Ceramic Implant (Neodent, Curitiba, Brazil) at various bone densities.

Density Pair	p-Value	Adjusted p-Value*
10 PCF – 15 PCF	0.056	0.334
10 PCF – 30 PCF	< 0.001	0.000
10 PCF – 40 PCF	< 0.001	0.000
15 PCF – 30 PCF	0.020	0.118
15 PCF – 40 PCF	< 0.001	0.004
30 PCF – 40 PCF	0.284	1.000

Bonferroni correction used to adjust for multiple testing.

The purpose of this investigation was to analyze how implant macrogeometry—specifically tapered versus cylindrical designs—and bone density interact to influence implant performance, thereby guiding clinicians in selecting implants suited for varying bone qualities.

For testing, polyurethane foam blocks were employed. This synthetic substrate, routinely used in biomechanical implant research, exhibits homogeneous mechanical behavior analogous to human cancellous bone, as outlined in ASTM guidelines [31]. Its uniformity minimizes biological variability and maintains mechanical consistency similar to the mineral portion of bone tissue, providing a controlled and reproducible model for comparative implant assessments [31, 32]. Nonetheless, this artificial medium cannot simulate thermal responses during drilling or histological characteristics of actual bone.

Implant stability was quantified using Resonance Frequency Analysis (RFA) with the Osstell® Beacon system [27], a method widely recognized for its simplicity, accuracy, and reproducibility. As noted by Kittur N *et al*. [26], RFA remains the most dependable technique for in vivo assessment of implant anchorage. In the present study, the Smartpeg™ transducer was attached manually. Despite operator-dependent variations in tightening force, prior findings confirm that manual fixation provides consistent and objective measurements [33].

The influence of implant geometry on early stability is well-documented. Unlike parallel-sided implants, tapered implants tend to create compressive forces on surrounding bone during insertion, promoting better load distribution and potentially increasing mechanical fixation [23, 24]. The current findings revealed statistically significant ISQ differences between both shapes, with the tapered configuration yielding higher resonance values and thus enhanced initial stability relative to the cylindrical form.

The Neodent® Zi Ceramic Implant (Neodent, Curitiba, Brazil) recorded ISQ values above 70 in the 30 PCF and 40 PCF density groups and values exceeding 60 at 15 PCF. As defined by Osstell® criteria [29], these correspond to high and moderate stability, respectively. Values below 60, associated with low stability, were noted mainly in 10 PCF for the Neodent® system and at 10 PCF and 15 PCF for the Straumann® Pure Ceramic Implant (Institut Straumann AB, Basel, Switzerland).

The available evidence on zirconia implant macrodesigns remains limited, making cross-comparisons with metallic systems difficult. Nevertheless, the outcomes of this experiment align with Barikani H *et al*. [34], who examined the influence of geometry, diameter, and length of titanium implants on stability via RFA, concluding that tapered implants consistently outperformed cylindrical ones regardless of dimensional variation.

Parallel results were observed by Comuzzi L *et al*. [35], who analyzed tapered and cylindrical titanium implants inserted in 10 PCF and 20 PCF polyurethane and found significantly greater stability for the tapered form in the lower-density group. A subsequent study simulating post-extraction sockets with the same densities confirmed that tapered implants demonstrated superior mechanical anchorage under all experimental conditions [36]. These findings were further supported by in vivo studies in dogs, where apically tapered titanium implants showed significantly higher mean ISQ values than cylindrical designs upon immediate placement [37]. In addition, García-Vives *et al*. [38]

compared tapered and cylindrical zirconia implants (10 mm) in type IV bovine bone, determining that the tapered geometry provided stronger fixation at insertion.

Clinical trials have produced similar patterns. In a prospective human study, Lozano-Carrascal *et al*. [39] compared 25 cylindrical and 22 tapered titanium implants, observing higher ISQ values for the tapered type—71.67 ± 5.16 in the mandible and 67.2 ± 4.42 in the maxilla. Rokn A *et al*. [40] attributed this advantage to the radial compressive effect generated by tapered implants during placement, recommending their use in sites with poor bone density or limited volume to enhance initial fixation.

Conversely, opposing results have been reported. Heitzer M *et al*. [41] compared tapered titanium and cylindrical zirconia (Straumann® Pure Ceramic) implants in cadaveric anterior maxillary bone and in polyurethane blocks (10 PCF and 20 PCF). Their results showed that cylindrical zirconia implants achieved higher mean ISQ values than the tapered titanium counterparts, suggesting that cylindrical zirconia represents a suitable alternative in low-density bone conditions.

Likewise, in an animal model, Bilhan *et al*. [42] reported higher ISQ readings for cylindrical titanium implants compared with tapered ones. They explained that, in cancellous bone, the tapered form relies primarily on the cervical region for anchorage, reducing apical support and potentially compromising total stability.

Nevertheless, evidence summarized in a meta-analysis [43] indicated no statistically significant difference between tapered and cylindrical titanium implants when ISQ was measured immediately post-placement. The authors highlighted the need for randomized controlled trials to clarify whether tapered implants provide measurable advantages in immediate loading or other complex clinical contexts.

Analysis of the impact of bone density on implant primary stability, reflected by ISQ measurements, revealed statistically significant variations, confirming that density directly affects stability in both implant configurations. The highest ISQ readings appeared at the 40 PCF level, which represented the densest substrate evaluated, for both the Neodent® Zi Ceramic Implant (Neodent, Curitiba, Brazil) and the Straumann® Pure Ceramic Implant (Institut Straumann AG, Basel, Switzerland). Overall, the data demonstrated a clear rise in ISQ values as bone density increased, establishing that greater density enhances initial fixation regardless of implant geometry.

In an in vivo experiment, Ivanova *et al*. examined the relationship between several factors—including bone density—and primary stability. Their research involved 90 implants placed in the maxilla and mandible of different subjects. Results indicated that ISQ scores rose proportionally with density, confirming that denser bone tissue promotes stronger initial implant anchorage [44].

This investigation has several limitations, such as the repeated insertion and removal of the same implants, reuse of a single SmartPeg™, employment of polyurethane foam blocks lacking cortical bone, and variations in implant dimensions.

The repetitive placement process could have modified the thread shape or surface structure, introducing variability in ISQ outcomes. This limitation was largely due to economic and logistical restrictions often present in dental implant research. Future experiments should consider using new implants for each trial to prevent this distortion.

The reuse of one SmartPeg™ per implant might also have led to minor wear of the aluminum interface or an imperfect fit, potentially affecting measurement precision. Clinically, such wear could cause improper seating of the abutment and release of aluminum debris, compromising the mechanical integrity of the connection [45].

Osteotomies were performed without irrigation in the present work. Nevertheless, findings by Di Stefano *et al*. indicated that irrigation during drilling in polyurethane test blocks does not influence stability parameters assessed via RFA [46].

An in vitro study by Chávarri-Prado *et al*. compared two polyurethane substrates—one with and one without a cortical layer—and found that the presence of cortical material significantly enhanced ISQ readings. Including a cortical-like surface here would thus have yielded a closer approximation of clinical bone conditions [47].

Operator skill may also have influenced the results. Literature indicates that clinical performance improves with experience, leading to refined technique, fewer complications, and higher success rates [48].

Discrepancies in implant length and diameter should also be considered. Research remains divided on their influence: some studies report that longer implants reduce initial stability [49], others suggest length increases it [50], and some find no measurable association [40, 51]. Hence, assumptions that larger implants inherently yield better fixation are likely oversimplified; thread design, implant contour, and bone quality may play more decisive roles.

To strengthen these observations, future research should adopt diverse experimental frameworks—such as animal or in vivo human studies and randomized clinical trials—to evaluate biological phenomena absent in laboratory settings, including bone regeneration, osseointegration dynamics, and healing patterns. Expanding sample size, exploring a broader range of densities, and comparing ceramic and titanium systems would enhance reliability. Additionally, testing implants with different geometries, sizes, and surface modifications could clarify which parameters most effectively improve outcomes, especially in low-density bone regions.

Conclusion

Within the boundaries of this in vitro analysis, the key findings are:

- Implant macrogeometry significantly affects primary stability in zirconia systems.
- Tapered implants consistently generated higher ISQ values than cylindrical models across every bone density tested.
- Increased bone density corresponded to greater mechanical stability.

Thus, when working in high-density bone, both implant types may achieve reliable fixation. Conversely, in less dense bone, a tapered configuration appears advantageous for obtaining superior primary stability. This is particularly relevant to the posterior maxilla, where lower density frequently complicates anchorage. In such scenarios, selecting a rough-surfaced, self-tapping titanium implant could further reinforce stability and represent a clinically preferable choice.

These conclusions may assist practitioners in tailoring implant selection to patient-specific bone characteristics, improving treatment predictability and minimizing the risk of implant loss.

For comprehensive verification, future investigations should include animal experiments, human trials, and randomized studies, which would offer deeper insight into how bone biology and implant design interact under real clinical conditions.

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