Original Article

The Influence of Implant Macro-geometry in Primary Stability in Low-Density Bone: An *in vitro* Study

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ABSTRACT

Aim: This study assessed the primary stability of implants featuring various geometries in polyurethane bone blocks simulating low-density bone types 3 and 4. **Methods:** The study included 36 implants divided into three groups (Straumann BLT, $n = 12$; Zimmer TSV, $n = 12$; and Dentium Superline [DSL], $n = 12$). Implants featuring three different thread designs, a tapered body, a diameter of 4.0–4.1 mm, and a length of 10 mm were inserted into polyurethane bone blocks (20 and 15 PCF) to simulate bone types 3 and 4. Primary stability was evaluated using implant stability quotient (ISQ), insertion torque (IT), and removal torque (RT). IT and RT were compared using ANOVA, while ISQ was analyzed using the Kruskal–Wallis test. A P value < 0.05 was considered statistically significant. **Results:** For bone type 3, the highest IT (30.21 ± 1.38 N cm) and RT (23.25 ± 2.30 N cm) value were observed for the Zimmer TSV, and the highest ISQ values (63.29 ± 0.54 N cm) were observed for DSL. For bone type 4, the highest IT (18.07 ± 1,71 Ncm) and RT (14.48 ± 1.81 Ncm) values were observed for the Zimmer TSV, and the highest ISQ values (58.46 ± 0.78 N cm) were observed for the DSL. The ISQ, IT, and RT values of the implant groups were significantly different ($P < 0.001$). **Conclusions:** Implant geometry and bone density were key factors influencing primary stability in this study. The outcomes of the present study may help clinicians make decisions, especially when dealing with bone that has a less favorable quality. These findings may have important clinical implications related to immediate or early loading protocols, highlighting the critical role of implant design in attaining sufficient stability.

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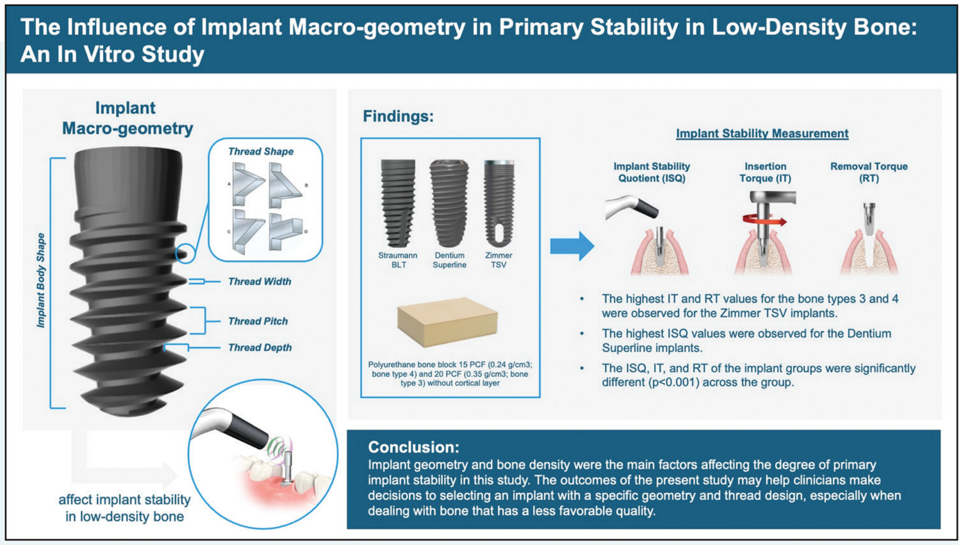

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Introduction

Implant osseointegration is the direct bond between the implant and bone, influenced by primary and secondary stability. Primary stability derives from the mechanical connection between the implant and osseous walls, whereas secondary stability emerges as new bone is generated throughout the healing process.[1] Implant stability is affected by bone density, implant geometry, and surgical techniques, with bone density being key to long-term success.[2,3] It is crucial to select implants with specific geometries and thread configurations to attain optimal primary stability in cases of poor bone quality or immediate implant placement. Low bone density increases the risk of early implant failure, and it can be challenging to attain primary stability.[4] Several factors can influence bone density, including age, sex, medical treatment, and systemic disease. However, the posterior maxillary region is clinically characterized by a lower bone density.[1] Achieving primary stability in cancellous bone, which is frequently found in the posterior maxilla, may be challenging, and this is related to an increased risk of failure.[3,5] Implant macro- and micro-geometries are essential for stability. Notwithstanding developments in the implant technology, the majority of manufacturers utilize tapered or cylindrical designs, with tapered implants demonstrating superior primary stability, as evidenced by clinical and *in vitro* investigations.[6-8]

Besides the implant design, the material used for preparation of dental implants influences primary stability. Implants are typically made from metals, ceramics, or polymers. Titanium and its alloys are the most commonly used implant materials due to their high biocompatibility and resistance to corrosion in physiological environments.[9] Moreover, the mechanical properties of titanium allow for the precise fabrication of different implant shapes and thread designs to ensure maximum implant stability. Alternative biomaterial agents like polyetheretherketone (PEEK) and zirconia are gaining popularity and can significantly impact dental implant success. The development of PEEK-based implants may offer a valuable metal-free alternative to conventional titanium implants.[10,11]

Based on previous studies, polyurethane materials are often used as synthetic bones to replace human bone in implant studies to investigate the influence of implant macro- and micro-geometries on primary stability *in vitro*.[12,13] The anatomical limitations and potential biases caused by variations in bone quality in implant osteotomies conducted on *ex vivo* materials, such as bovine bone and cadaveric bone, can be mitigated through *in vitro* simulation with polyurethane bone blocks. Polyurethane bone blocks are preferred for performing comparative mechanical tests on various implant designs due to their uniform characteristics and homogeneity. Furthermore, polyurethane bone blocks can be produced in various densities and thicknesses, enabling them to replicate the diverse characteristics of bone tissue in different regions of the maxilla and mandible.[1]

Currently, numerous commercial implant brands differ in shape, size, diameter, surface treatment, and prosthetic connection to accommodate various clinical conditions. However, the lack of knowledge about bone density and optimal macro-geometry, including thread configuration to obtain optimal primary stability at the implant–bone interface, complicates dentists' ability to plan surgeries and select an appropriate implant design. Additionally, there is insufficient research on innovative implant designs that specifically address the challenges of low bone quality. Therefore, it is crucial for researchers to explore new implant materials and designs to overcome the limitations posed by surgical techniques and the bone quality and quantity available for implantation.

This study aimed to evaluate the primary stability of three dental implant geometries by measuring implant stability quotient (ISQ), insertion torque (IT), and removal torque (RT) values to determine the best option for low-density synthetic bone that represents the human posterior jaw structure. The null hypothesis was that there were no significant differences in the IT, ISQ, and RT values across implant geometry in low-density bone.

Materials and Methods

Implants

This study included three groups of implants based on design: Straumann BLT (SBLT), Zimmer TSV (ZTSV), and Dentium Superline (DSL) groups [Figure 1]. Implants selected in this study were recommended by the manufacturer for use in low-density bone and immediate loading. The implant brands used in this study vary in their macro-geometries, including a thread configuration that offers unique designs and thread patterns specifically designed for compromised bone, which can affect the stability at the implant–bone interface. The characteristics, including thread geometry and surface texture, have varied since this study used commercially available implants to mimic clinical settings [Table 1]. A hole was drilled into the polyurethane bone block following the manufacturer's instructions. After drilling, the implant was placed, and the maximum IT, ISQ, and RT values were measured. All implants were inserted by a clinician according to the manufacturer's protocol.

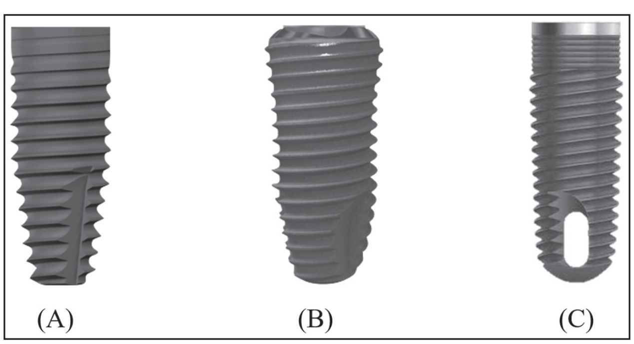

Figure 1: Close-up images showing the detailed characteristics of the investigated implants. (A) Straumann BLT,[14] (B) Dentium Superline, and[15] (C) Zimmer TSV[16]

Polyurethane bone blocks

The ASTM F-1839-08 recognized polyurethane as a standard material for bone simulations for *in vitro* studies and orthopedic implant evaluation.[17] Polyurethane bone provides a uniform substrate for testing, which is beneficial for controlling experimental conditions. However, human bone is heterogeneous, with variations in density, structure, and quality across various anatomical sites and among individuals. This study utilizes two densities of polyurethane to better simulate the variety of bone characteristics observed in clinical practice and address the limitations of using a single type of polyurethane. This study implemented standardized protocols for implant site preparation and insertion techniques to mitigate potential biases related to experimental design. A controlled drilling and testing machine ensured precise drilling without the influence of manual error and minimizing variability. Two types of rigid polyurethane bone blocks (SYNBONE SDN BHD, Malaysia) were used in this study, with densities of 20 PCF (0.35 g/cm³) and 15 PCF (0.24 g/cm³). These densities correspond to bone types 3 and 4, respectively. The polyurethane bone blocks were rectangular and measured 5 cm × 5 cm × 5 cm, and their homogeneous densities allowed a standardized investigation of the type of bone and facilitated a comparison of the screws based on their geometry.[12]

Insertion torque (IT) and removal torque (RT)

The IT (N cm) represents the maximum force applied in the clockwise direction, which causes bone stripping. The RT (N cm) measures the force required to remove the implant from the bone. After calibration of the device, a single person measured the IT and RT (N cm) values using a testing machine manufactured by Hung Ta Instrument Co., Ltd

Resonance frequency analysis (RFA)

Primary stability was assessed using an resonance frequency analysis (RFA) device with MultiPeg (Osseo 100+, NSK, Japan). The ISQ values range from 0 to 100. RFA was conducted twice for each specimen in the buccal and mesial, and average ISQ values were computed. Calibration was done using a 4 × 10-mm

Table 1: Geometric characteristics of the implants used in the current study

Implant Characteristics			
Commercial Name	**Straumann BLT**	**Dentium Superline**	**Zimmer TSV**
Implant body	Tapered	Tapered	Tapered
Body diameter	4.1	4.0	4.1
Apical diameter	1.8	3.8	3.5
Length	10	10	10
Thread	Single thread	Double thread	Triple-thread
Thread shape	Reverse buttress	Reverse buttress	V shape
Thread pitch	0.8	1.8	0.6
Thread Depth	0.3	0.40	0.36
Micro-thread	None	None	Yes
Self-cutting	Yes	Yes	None

All measures are provided in mm.

Table 2: Comparison of ISQ, IT, and RT values of the implant and bone types

Bone Type	Stability	Implant Type			*P* value
		Straumann BLT (SBLT)	Zimmer TSV (ZTSV)	Dentium Superline (DSL)	
Type 3	IT	26.50 ± 2.36	30.21 ± 1.38	22.90 ± 1.60	<0.001
	RT	21.43 ± 1.59	23.25 ± 2.30	14.23 ± 2.33	<0.001
	ISQ	61 ± 0.52	60.88 ± 0.38	63.29 ± 0.54	<0.001
Type 4	IT	10.93 ± 0.34	18.07 ± 1,71	10.37 ± 1.15	<0.001
	RT	8.86 ± 1.02	14.48 ± 1.81	6.34 ± 0.74	<0.001
	ISQ	57.33 ± 1.05	55.70 ± 0.58	58.46 ± 0.78	<0.001

implant in the same bone block before the protocol. The MultiPeg was manually attached, and ISQ measurements were recorded three times each day.

Statistical analysis

The sample size was calculated based on the study by Soror *et al.,*[18]with effect size (f) of 0.57, α of 0.05, β of 0.2, and power of 80%, resulting in 33 samples. It was increased by 10% to compensate for potential dropouts or missing data, resulting in 36 samples, with 12 samples in each group. G*Power 3.1 was used to determine the sample size. The distribution and homogeneity of data were examined, and the correlation between implant stability and bone type was evaluated. Descriptive data were collected for each type of implant. IT and RT values were analyzed using one-way ANOVA, whereas ISQ data were assessed using the Kruskal–Wallis test, accompanied by *post hoc* analyses. Statistical analysis was conducted using SPSS Statistics 22.

Results

The IT, RT, and ISQ values differed significantly across the groups (all $P < 0.001$), as summarized in Table 2 and Figure 2. The ZTSV group had the highest IT, followed by the SBLT group. The DSL group, on the other hand, had the lowest IT. The highest RT was observed for the ZTSV group, followed by the SBLT group, and the DSL group had the lowest value. The highest ISQ was observed for the DSL group, followed by the SBLT group, and the ZTSV group had the lowest value. Table 3 *post hoc* analysis showed significant differences in IT values for bone type 3 ($P < 0.001$) and RT and ISQ values for bone type 4 ($P < 0.001$). No significant differences were found between IT values of the SBLT and DSL groups for bone type 4 ($P = 0.337$), RT values of the SBLT and ZTSV groups for bone type 3 ($P = 0.126$), and ISQ values of the SBLT and ZTSV groups for bone type 3 ($P = 0.270$). Table 4 showed a significant positive correlation between primary stability (IT, RT, and ISQ) and bone density across all implant types, indicating that higher bone density is associated with increased stability.

Discussion

The study hypothesis was rejected as the primary stabilities of the different implant systems were not equal. Primary stability is crucial for osseointegration, ensuring direct bone contact with the implant, preventing connective tissue formation, and promoting long-term stability. This facilitates the optimal distribution of masticatory functional loads and promotes bone formation. Studies have focused on implant design to enhance primary stability and increase the predictability of osseointegration,

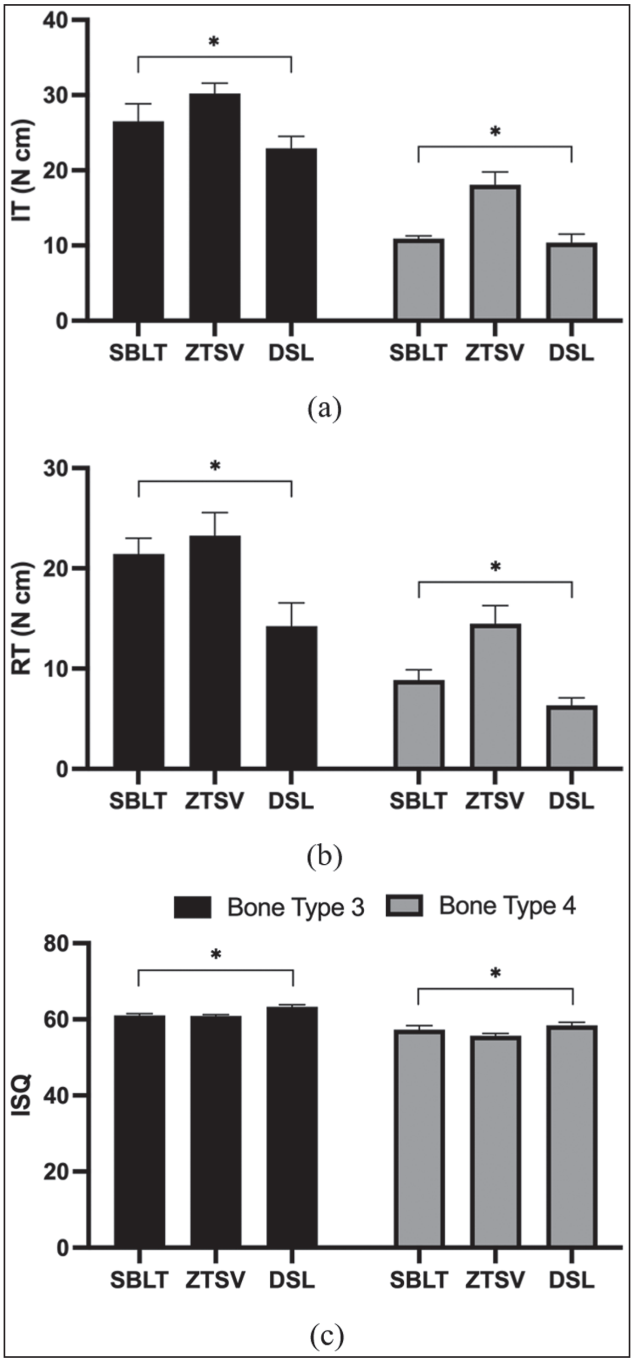

Figure 2: Bar chart showing the comparison of (a) IT, (b) RT, and (c) ISQ values across implants (* $P < 0.05$)

particularly in low-density bones where sufficient anchoring is challenging to attain.[12,19,20] This study assessed the primary stability of three different implant designs for the type 3 and type 4 bone models. The focus was to determine the more effective implant design for compromised situations, where bone quality is critical for achieving high initial fixation. Bone quality is an inherent characteristic that cannot be changed, and it is necessary to modify the design and surface texture of implants to match with particular characteristics of the host bone to enhance osseointegration.[1,18] In dense bones, implants can attain similar initial stability regardless of their design. However, differences in implant designs can affect primary stability in less dense bones. Less dense bones have lower bone-to-implant contact, increasing the risk of early failure. Therefore, selecting an implant design that maximized the contact area may improve mechanical anchoring and primary stability in low-quality bones.[21,22]

The geometric features of the implant thread, including its shape, width, depth, pitch, and face angle, have an impact on the distribution of biomechanical loads on the implant.[23,24] Thread shapes include square, V-shaped, buttress, and reversed buttress. Implants with buttress and square threads mainly distribute axial compressive forces. In contrast, V-shaped and reversed buttress threads convert axial forces into shear, tensile, and compressive forces. It is essential to design implant threads to maximize surface contact area, optimize beneficial forces, and minimize adverse stimuli. Recently, researchers used finite element analysis (FEA) to understand how these geometric characteristics affect the load distribution in the surrounding region.[25,26] Several studies using FEA have shown that implants with V-shaped threads and broader square threads generate less stress than narrow square threads in cancellous bone. The thread shape, linked to the face angle, shows that V-shaped threads with a 30° angle generate higher shear forces than reverse buttress threads with a 15° angle.[27]

Implant stability can be evaluated using invasive methods (e.g., histology, histomorphometry, RT, and pullout tests) and noninvasive methods (e.g., IT, percussion test, periotest, and RFA).[28,29] RFA and IT are the most frequently used techniques in clinical settings to assess primary stability and gather data to evaluate the implant stability.[5,30,31] IT refers to the rotational force required for the screw to move forward into the mounting hardware. It serves as a reliable indicator of the local bone quality and primary stability achieved during surgery. The IT evaluates implant stability by measuring the stiffness at the bone–implant contact during or after installation. This method is highly efficient and has minimal contraindications for assessing primary stability.[1,12] RFA is an effective method for evaluating implant stability by detecting the micromovements of the implant within the bone.[1,31]

The ISQ values for bone types 3 and 4 were in the following order: DSL > SBLT > ZTSV. The ISQ value was significantly higher in the DSL system than that in the other systems. This is probably related to the double

Table 3: Comparison of the insertion torque, removal torque, and implant stability quotient values using the *post hoc* test

Stability Parameter	Bone Type	Implant Type	*P* value
Insertion Torque	Type 3	SBLT vs. ZTSV	<0.001
		SBLT vs. DSL	<0.001
		ZTSV vs. DSL	<0.001
	Type 4	SBLT vs. ZTSV	<0.001
		SBLT vs. DSL	0.337
		ZTSV vs. DSL	<0.001
Removal Torque	Type 3	SBLT vs. ZTSV	0.126
		SBLT vs. DSL	<0.001
		ZTSV vs. DSL	<0.001
	Type 4	SBLT vs. ZTSV	<0.001
		SBLT vs. DSL	<0.001
		ZTSV vs. DSL	<0.001
Implant Stability Quotient	Type 3	SBLT vs. ZTSV	0.270
		SBLT vs. DSL	<0.001
		ZTSV vs. DSL	<0.001
	Type 4	SBLT vs. ZTSV	<0.001
		SBLT vs. DSL	0.008
		ZTSV vs. DSL	<0.001

Table 4: Relationship between IT, RT, and ISQ and bone density in all implant types

		Implant Type		
		SBLT	ZTSV	DSL
R^2	IT	0.959	0.943	0.957
	RT	0.960	0.830	0.850
	ISQ	0.842	0.968	0.934

thread and 0.4 mm thread depth, which increases the functional surface area and bone contact. This finding is consistent with the report of studies conducted by Reinaldo *et al*[32] and Cucinelli *et al.*,[33] which demonstrated that implants with a greater thread depth had higher ISQ values than those with a lower thread depth. The research conducted by Menini *et al.*[34] showed that implants with deeper threads demonstrate higher primary stability and might be useful in immediate loading rehabilitation. Furthermore, deeper threads increase the surface area, offering an advantage in cases of poor bone density by improving bone-to-implant contact and enhancing primary stability.[32] Bone growth between threads increases resistance to occlusal and tensile forces, improving primary stability, enhancing the implant–bone connection, and leading to better osseointegration and higher implant success.[10,35] In addition, the DSL implant contains a self-cutting blade in the half-apical part. The study has demonstrated that self-cutting blade designs offer improved initial stability and are recommended for osteoporotic or type 4 bones.[36,37]The present study aligns with Falco *et al.*,[38] who found that self-cutting implants with wider threads have higher ISQ values and provided greater primary stability than implants with a narrower thread design, especially in cases of peri-implant deficiencies or low-density bone.

In this study, the IT was recorded to assess the primary stability. IT is associated with implant micromotion.[39] Research indicated that optimal IT ranges between 30 and 35 N/cm in low-density bone are associated with bone growth and bone–implant contact.[40] Implant micromotion should range between 10 and 150 µm since excessive micromotion may compromise osseointegration.[41] In this study, the IT for the type 3 and 4 bones was greatest for the ZTSV implants, followed by the SBLT and DSL implants. The ZTSV implants showed the highest IT for bone types 3 (mean = 30.21) and 4 (mean, 18.07), which could be the result of the triple-thread design and smaller thread pitch. The ZTSV implant uses a triple thread, which can affect insertion speed and stability. Double- and triple-threaded implants can be inserted faster and provide greater primary stability. This makes them suitable for immediate loading due to their increased surface area compared to single-threaded implants.[11,21] The effect of this macro-design is consistent with those reported by Yamaguchi *et al.*[21] and Soror *et al.*[18] Furthermore, a ZTSV implant with a smaller thread pitch can enhance the initial mechanical stability for cases of poor bone quality. An implant with a smaller thread pitch enables a larger contact area between the implant and bone, resulting in enhanced mechanical interlocking and increased resistance during insertion.[21,42] The results of this study are consistent with those of the research conducted by Benalcázar-Jalkh *et al.*,[35] which concluded that implants with larger surface areas have higher IT values.

Previous studies have demonstrated a positive correlation between IT and RT. RT increases with increasing IT, which suggests better primary stability and osseointegration.[40,43] The low RT of the DSL implants may be associated with the self-cutting design of the apical part. This finding is similar to the report by Tumedei *et al*. which showed that the RT value is lower for implants with self-cutting blades in half-apical parts.[4] This present study found that the RT was lower than IT for all the implant systems. This could be related to the deformation and compression of the adjacent bone structure due to lateral forces during implant placement.[44]

Recent clinical trials have highlighted the impact of implant geometry and thread design on primary stability in low-density bone. Supachaiyakit *et al*.[45] found that tapered implants exhibited higher ISQ values and better primary stability compared to cylindrical implants in low-density bone. Another randomized clinical trial by Barbosa *et al*. showed that V-shaped threads offered better primary stability than square threads. This finding indicates that thread design is essential for optimal stability, especially in difficult bone conditions.[46] Olmedo-Gaya *et al*. emphasized the impact of various surgical techniques on primary implant stability in the posterior maxilla, characterized by poor bone density and complex morphology. The study indicated that various surgical techniques significantly impacted primary stability. Implants inserted using the under-preparation technique demonstrated superior IT and ISQ values relative to those inserted with conventional instrumentation. Modifying surgical techniques may enhance primary stability, especially in conditions involving low-density bone.[47]

The result of this study suggests that clinicians should opt for tapered implants with deeper threads and double- or triple-thread features when addressing cases of reduced bone density, particularly in the posterior maxilla. The findings of this study suggest that implants without self-cutting blades exhibit higher IT, potentially resulting in enhanced implant stability. Furthermore, using IT and RFA as reference tools for monitoring is advisable to assess short-term changes. The clinical implications discussed are based on exploratory data and may not accurately represent clinical reality. Future research must validate current biomechanical findings through clinical validation.

Moreover, the patient's systemic health issues, including osteoporosis, which significantly affects bone density and strength, complicate the implant placement. Osteoporosis could be a risk factor for osseointegration, jeopardizing the healing process and bone remodeling.[48] Bone density and quality are affected by numerous factors, including hormonal levels, vitamin intake, and the mechanical characteristics of bone. Comprehending these relationships is essential for improving bone health and averting diseases like osteoporosis. Hormones have a crucial role in the efficacy of dental implant treatment through their influence on bone remodeling. Hormones, including parathyroid hormone (PTH), growth hormone, and sex hormones (estrogens and androgens), profoundly impact bone metabolism, hence directly affecting the healing and osseointegration of dental implants.[49] Therefore, strategies such as preoperative assessment and hormonal evaluation, using advanced imaging techniques for bone evaluation, and customized implant design may be proposed to enhance the clinical application of dental implants, particularly for patients with low-density bone. Cone-beam computed tomography facilitates a comprehensive assessment of bone density and quality before implant placement.[50] This imaging technique assists clinicians in identifying regions of low bone density and facilitates appropriate planning.[51] Integrating sophisticated imaging into treatment planning enables clinicians to make better decisions about implant selection and placement procedures, improving patient outcomes. The development of customized patient-specific implants based on an individual's bone density profile involves the design of implants using specific thread configurations and enhanced surface treatments for low-density bone. Combining advanced techniques, customized designs, and multidisciplinary approaches will address the issues associated with low bone density, improving the clinical results.

The current study had certain limitations. While polyurethane bone blocks have been used in previous *in vitro* studies to assess the primary stability of dental implants, there are notable differences between polyurethane and actual human bone that must be acknowledged when interpreting research outcomes. Polyurethane does not fully mimic the biological and structural complexity of human bone. Human bone is a living tissue that undergoes continuous remodeling and has a unique microstructure characterized by osteocytes, blood vessels, and a mineralized matrix. In contrast, polyurethane is a synthetic material lacking these biological characteristics, potentially affecting the implant's osseointegration. Moreover, in clinical situations, factors such as the thickness of cortical bone, anatomical variations, surgical technique, and the surgeon's experience can significantly affect implant placement and stability. Patient-specific factors, including age, medical conditions (such as diabetes or osteoporosis), and healing capacity, significantly influence the success of implant rehabilitation. Additional factors, including the healing environment surrounding an implant, such as vascularization, inflammatory response, and growth factors, are crucial in osseointegration. The discrepancies between *in vitro* findings and clinical realities highlight the necessity of validating research outcomes through comprehensive clinical investigation considering the biological, anatomical, and patient-specific factors. This study exclusively investigated the primary stability; the influence of secondary stability and cellular responses on the healing period after implant placement was not assessed. Nevertheless, further clinical trials are required to evaluate the primary and secondary stability for more precise outcomes.

Conclusions

Considering the limitations of the current study, ZTSV implants had the highest IT and RT values for bone types 3 and 4, while DSL implants had the highest ISQ values. These findings cannot be generalized to clinical practice until further clinical investigations are conducted. Clinicians should consider the specific design features of the implant, including the thread configuration, when selecting an implant for a patient. Tapered implants featuring deeper and more aggressive threads with double- or triple-thread designs are advised, particularly for patients with compromised bone quality, as they provide enhanced engagement and superior primary stability. A comprehensive assessment of implant design is essential, particularly for immediate or early loading rehabilitation. Successful implant placement in patients with low-density bone requires understanding of the bone healing process, careful selection of surgical techniques, and thoughtful consideration of implant design to optimize treatment outcomes.

Conflict of interest

There are no conflicts of interest.

Patient declaration of consent

Not applicable.

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Author contributions

FA: data collection, laboratory work, conceptualization, and manuscript preparation. SS: conceptualization, data interpretation and proofreading of manuscripts. RSD: conceptualization, laboratory supervision, data interpretation, and proofreading of manuscripts.

Data availability statement

Not applicable.

Ethical policy and institutional review board statement

Not applicable.

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List of Abbreviations

IT Insertion torque
ISQ Implant stability quotient
RT Removal torque
RFA Resonance frequency analysis

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